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A REVIEW OF VAPOR EXTRACTION TECHNOLOGY FOR
CONTAMINATED SOIL REMEDIATION

by

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REPORT

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1.0 Introduction

1.1 Introduction

Over the past several decades, awareness of the health and environmental risks arising from hydrocarbon contamination of soil and groundwater has increased dramatically. Legislation enacted in the 1970's and 80's signaled the beginning of a new environmental policy created to deal with these significant problems. Along with this legislation came the creation of agencies at the federal, state, and local level to implement and enforce these legislative mandates. Unfortunately, passing laws to clean up sites is a much easier task than the actual cleanup. Many of the criteria established for the cleanup of sites that posed significant health risks did not take into account any practical implementation of these requirements. The major problem that has slowed the well intentioned mandates for cleanup of environmental contamination has been the development of technologies which can effectively and cost-efficiently meet these criteria.

Typical contamination sites include manufacturing plants, petroleum refineries, fuel and chemical storage facilities, and gasoline service stations. Soils at these sites can become contaminated in a number of ways with such volatile organic compounds (VOCs) as industrial solvents and petroleum components. The widespread use of VOCs in the manufacturing of pesticides, plastics, paints, pharmaceuticals, solvents, and textiles is the main reason VOCs are one of the most common contaminants found today. Sources of contamination include intentional disposal, application of pesticides in agricultural practices, landfill disposal of organic wastes from manufacturing processes, accidental spills and leaking underground storage tanks (UST). Specific

regulations requiring the investigation of UST's, which are prevalent at gasoline service stations, have identified literally thousands of sites which are contaminated with petroleum hydrocarbons. Contamination of groundwater from these sources can continue even after discharge has stopped because the unsaturated zone above the groundwater aquifer can retain a portion or all of the contaminant discharge. Remediation of a VOC impacted site can never be complete so long as contaminants remain in the unsaturated zone.

Effective remediation of sites contaminated with VOCs requires a sound understanding of regulatory issues, technology options, and the site hydrogeology. Alternatives for decontaminating unsaturated soil include excavation with on-site or off-site treatment or disposal, biological degradation, and soil flushing. None of these options is a cure-all for every situation. The optimal solution may often be a combination of several technologies. Only through a thorough site specific characterization, followed by a feasibility study that evaluates the various treatment alternatives, can a cost-effective treatment system be design that is best suited to the individual site.

A technology that is increasingly being used for the remediation of VOC contaminated sites is soil vapor extraction. Soil vapor extraction, also known as soil venting and soil air stripping, allows remediation of VOC contamination without the need for excavation. In soil vapor extraction, a vacuum pump or blower moves air through the soil near the contaminated zone. As contaminated air is removed, cleaner air moves through the soil to replace it. This air movement also promotes microbial degradation of contaminants at many sites. The contaminated vapors are vented to the atmosphere, treated, or destroyed in aboveground facilities. Some of the advantages of

the soil vapor extraction process are that it minimally disturbs the contaminated soil, it can be constructed from standard equipment, it can be used to treat larger volumes of soil at much greater depths than are practical with excavation, and it has the potential for product recovery. Soil vapor extraction is often use in conjunction with other treatment technologies.

1.2 Applications

Soil vapor extraction is often preferable to soil excavation, flushing or capping because it limits the amount of exposure of personnel, destroys or stabilizes contaminants rather than relocate them, and it can stimulate biodegradation of the contaminant. If a spill has penetrated more than about 20 or 30 feet or if the spill volume is over 500 cubic yards, excavation cost may exceed those associated with vapor extraction systems . Furthermore, soil vapor extraction is one of the few feasible technologies for soil remediation if contamination is located at depths greater than 40 feet (Hutzler, Murphy, & Gierke 1989). Vapor extraction is most applicable to the remediation of the higher volatile or lighter molecular weight constituents. These include contaminants such as trichloroethylene and gasoline constituents such as benezene, toluene, and xylene. As a general rule, the heavier fractions of hydrocarbons, such as diesel fuel and fuel oils, are not candidates for vapor extraction.

Optimum soil condition for soil vapor extraction include dry, permeable, uniform soils with relatively low organic content. Vapor extraction relies on a well distributed flow of air through the contaminated zone. High soil moisture contents and a large percentage of fines such as silts and clays will limit the permeability of the soil and thus the air flow. However, clays should not be automatically excluded. Gibson

(1993) had successful results in remediating clays using vapor extraction. Again, the permeability of the soil will dictate how quickly and successfully contaminants are remediated.

There is no cookbook list of site and contaminant characteristics that can be applied when evaluating whether soil vapor extraction will be effective. Any combination of parameters may make vapor extraction feasible. Often times it will come down to a decision by the designer or owner based on experience and the time constraints placed on the project.

1.3 Purpose and Scope

The purpose of this report is to provide a review of current information available on soil vapor extraction technology and its application in the remediation of sites contaminated with VOCs. This report will present information on site characterization procedures to determine if vapor extraction is feasible, typical design consideration for a vapor extraction system, and methods for enhancing this technology to incorporate its use with a wider range of contaminants and soil conditions.

2.0 Preliminary Planning and Contaminant Area Characterization

2.1 Introduction

Although this paper addresses a specific remediation technology, soil vapor extraction, the first step in any soil and groundwater remediation project is the remedial planning and investigation phase. Before a specific technology is selected and large sums of money invested in a remediation program, a thorough process of regulatory investigation and contaminant and site characterization must be completed. This approach provides a basic road map for the engineer which will allow the evaluation of all relevant factors in the decision-making process. Often times, the cost of project planning, site investigation, and design will approach the actual cost of remediation which can initially be hard to understand for a facility owner. However, these steps are an important part of the entire remediation process that must be properly completed in order to make intelligent decisions on remediation alternatives. This situation is typical of many engineering projects.

The owner often seeks to control project costs by limiting the preliminary investigation. All too often, this leads to expensive modifications during the course of a project. This situation is magnified in the case of environmental remediation where cleanup procedures may be ineffective and result in beginning the entire process over again. A thorough understanding of the system variables involved can enable the engineer to make intelligent decisions about remediation techniques as well as providing the owner with a realistic assessment of expected results in terms of complying with the applicable regulatory requirements for cleanup.

2.2 Remedial Planning

2.2.1 Regulatory Compliance

A practical understanding of cleanup regulations and agency policies is necessary for an effective site remediation program. Often more than one agency's regulations may apply to the cleanup of a site. In the case of multiple regulations from various agencies, the most stringent apply with two exceptions: if the remediation is voluntary, it may be exempt from some requirements, and a risk assessment may sometimes justify relaxing certain regulatory mandates.

The major federal regulations for hazardous waste cleanup are the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Superfund Amendments and Reauthorization Act (SARA), and the Resource Conservation and Recovery Act (RCRA). A site owner may also need to contend with state and local regulations. An example of the maze of regulations that can be encountered just on the federal level is the compliance criteria for remediation in terms of applicable or relevant and appropriate requirements (ARAR's). The USEPA defines ARAR's as 'applicable' referring to promulgated, legally enforceable laws and statutes that specifically address waste substances or pollution. 'Relevant and appropriate' (it must be both) refers to promulgated laws and statutes that relate to situations sufficiently similar to the particular waste situation and that are well suited to the situation. This type of applicability criteria can bring about a myriad of new compliance requirements. An additional concern that must be addressed early on is permitting considerations since this could affect possible treatment solutions. Many states require air permits to regulate air discharges, a major concern for a vapor

extraction system, and groundwater treatment of hydrocarbon-contaminated sites can also affect existing permits.

Understanding regulatory requirements and their application can impact the entire planning process. Specific categories of regulations may only be reasonably considered during certain periods of the planning process. Location-specific regulations can be assessed for their impact early on while cleanup technology related regulations will be considered during later stages of the process.

2.2.2 Remedial Planning and Implementation

With the framework of compliance regulations in place, the remedial planning and implementation phase can begin. This methodology is a five step process as shown in Figure 2.1. The first step is a preliminary inspection and assessment which includes a complete background review and a site screening. This involves assembling historical operations records, as-built drawings, old plot plans and boring logs, engineering drawings including utility locations as well as interviewing site personnel and past employees. This information is used to help identify the contaminant, probable sources of release, the zone of contamination and potentially impacted areas (neighbors, water supplies, etc.). Preliminary site screenings should also be used to roughly define the zone of contamination and site geology. With this information, a site model can be started which will begin to detail sources, pathways and receptors.

The next step in the process is the remedial investigation/feasibility study. In this step, a detailed site and contaminant characterization is completed along with conducting a preliminary risk assessment. At this point, various treatment methodologies are identified. In choosing a remediation technology, it is important to realize that

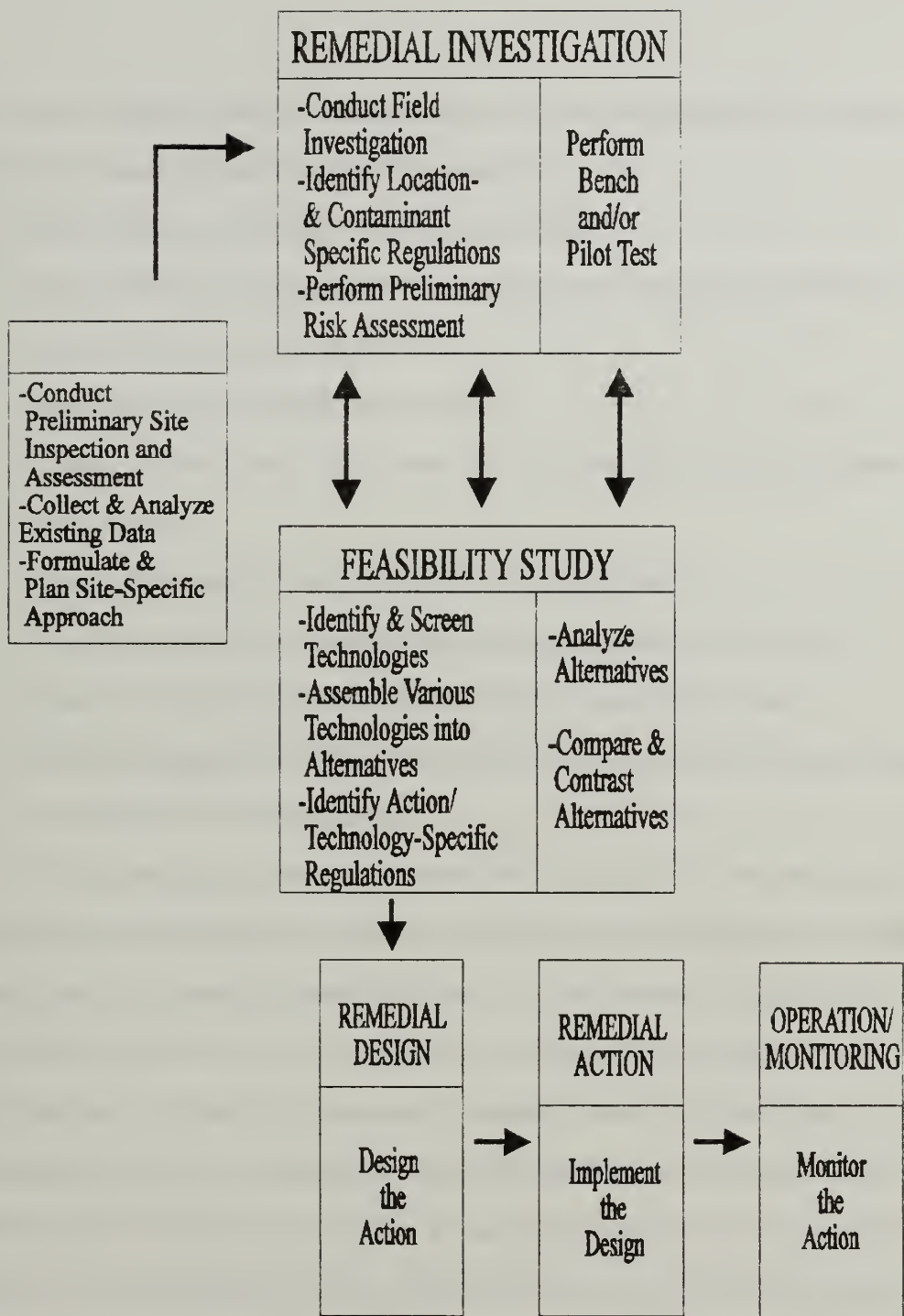


Fig. 2.1 Schematic of the remedial process (Daniel 1993).

there is no "cookbook solution." Each site poses its own challenges, which must be dealt with by answering such site-specific questions as:

- How much soil or groundwater requires cleanup?
- Must contaminants be excavated and treated aboveground or can they be treated using in situ methods?
- How much time is available for cleanup?
- Can air emissions and waste streams be minimized by combining treatment technologies?
- How will cleanup (or no cleanup) affect site neighbors?
- To what extent must a combination of technologies be pilot tested or otherwise demonstrated to agencies that must approve their use?
- Can technologies be combined to optimize treatment efficiency, meet cleanup standards, and minimize costs?

As one develops an accurate picture of the contaminant and the site, possible remediation methods begin to emerge. It is here that the feasibility study and remedial investigation phase interact as shown in Figure 2.1. This interaction is necessary in order to allow findings from the investigation to be used in the feasibility study considerations. As additional information for a specific study is required, the investigation can focus on obtaining this data. The feasibility study should include establishing clear objectives, assembly of technology options into alternatives and an evaluation and comparison of these alternatives. Pilot studies may be used to assist in the evaluation.

The final three phases are processes that are well defined in engineering practice; however, several issues require attention. Additional design investigations

may be required to confirm or refine existing site data. Refined performance criteria through pilot tests may be required. Obtaining site access and permitting will need to be completed. This can often times be one of the most difficult parts of the design process since permitting may require public hearings where remediation decisions will have to be justified. The health and safety of all personnel involved along with neighbors will be a major focus of these hearings and should be well thought out before hand.

2.2.3 Summary

The previous discussion on remedial planning is by no means a complete guide to the planning process. The remediation planning process is very complex and most often is time consuming and expensive. Various computer based decision models are available which ask the user for information, access data bases containing facts, and provides specific advice based on uncertain and incomplete information (Penmetsa and Grenney 1993). An advantage to this system is that through its knowledge base, it can guide a less-experienced engineer through a process that will reach a similar solution that would have been reached by a more experienced engineer under similar circumstances.

The focus of this chapter so far has been on the general planning process for a site remediation project. To specifically address soil vapor extraction systems, many of the steps discussed above will be focused on and analyzed in more detail. All waste sites involve both physical and chemical conditions that will influence remediation. These conditions, applied specifically to soil vapor extraction, can be broken down into system variables which must be recognized and evaluated during the planning and design process and are shown in Table 2.1.

Table 2.1 Variables in Soil Vapor Extraction Systems

Site Conditions

Distribution of VOC's
Depth of Groundwater
Surface Cover
Location of heterogeneities
Temperature, humidity
Atmospheric pressure
Location of structures
Rainfall

Control Variables

Air withdrawal rate
Vent configuration
Extraction Vent spacing
Vent spacing
Ground surface covering
Pumping duration
Inlet air VOC concentration and moisture content

Soil Properties

Permeability (air and water)
Porosity
Organic carbon content
Soil structure
Soil moisture characteristics
Particle size distribution

Response Variables

Pressure gradients
Final distribution of VOC's
Final moisture content
Extracted air concentration
Extracted air moisture
Extracted air temperature
Power usage

Chemical Properties

Henry's Law constant
Solubility
Adsorption equilibrium
Diffusivity (air and water)
Density
Viscosity

These variables will be discussed in more detail in the remainder of this chapter and in Chapter Three which discusses design procedures.

2.3 Background on Volatile Organic Compounds and Soil Vapor Behavior

VOC's released into the subsurface environment are acted upon by numerous forces that influence the degree and rate at which they migrate from the source. The extent to which the released contaminant partitions into the vapor phase is dependent

upon the characteristics of the VOC and the elapsed time since the release occurred. The manner in which the released product behaves in the subsurface will have a significant bearing on whether soil vapor extraction could be an approach for the site under consideration.

When a VOC is spilled or leaks from a source into the soil, it partitions among the liquid and vapor phases and becomes dissolved in soil water and absorbed onto the surfaces of soil minerals and organic matter. The partitioning among these four components as shown in Figure 2.2, will depend on the temperature, volatility and water solubility of the compound, the soil moisture content, as well as the type and amount of soil solids and the soils sorptive ability, i.e. mineralogy and organic content. Note that partitioning from a VOC to a soil solid is a one way process. The distribution of a VOC among the four components will vary with changes in site-specific conditions and will also change over time in response to weathering.

2.3.1 Volatilization

Volatilization of organic chemicals from ground water and within the vadose zone plays an important role in the transport of organic chemicals. The volatility of a compound is controlled in large part by the quantity present as vapor in the soil pores. Volatility is perhaps the most important characteristic affecting applicability of soil vapor extraction to that compound. Volatilization involves the partitioning of a VOC between pure liquid and soil gas and between soil gas and soil moisture. These two sequences are driven by two factors, the vapor pressure and Henry's Law. Vapor pressure is the pressure exerted by the vapor of the chemical in equilibrium with its pure solid or liquid form. At equilibrium, the mole fraction of a VOC in the air space above the pure liquid VOC at a specified temperature is expressed as:

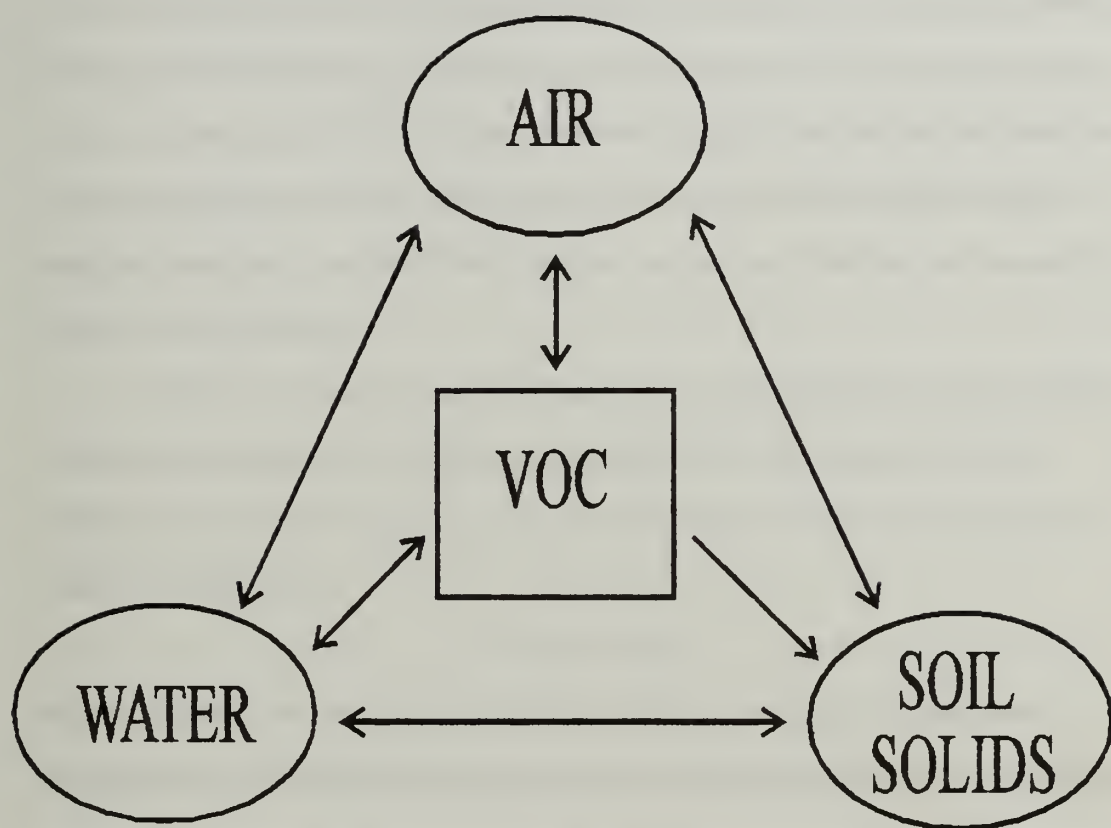


Fig.2.2 Partition diagram for a VOC.

$$y_a = p_a/p_t$$

where y_a is the mole fraction of chemical a, p_a is the vapor pressure of chemical a, and p_t is the total pressure in the air space. Generally, compounds with vapor pressures of less than 10^{-7} mm Hg are not volatile and are not removed by soil vapor extraction; vapor pressures above 0.5 mm Hg are removed to a significant degree and these are the compounds for which soil vapor extraction is most generally applied. Many gasoline constituents have sufficiently high vapor pressures that they can be removed by soil vapor extraction.

Henry's Law governs the volatilization from a contaminant in solution, rather than from a pure product. Partitioning between the VOC in soil gas and VOC dissolved in soil moisture may be expressed as K_H , the ratio of its concentration in each of the two phases.

$$K_H = C_G/C_L$$

where C_G is the concentration of the VOC in soil gas, and C_L is the dissolved concentration of the VOC in the water phase. At equilibrium, this ratio is constant for constant temperature and is referred to as Henry's Law constant. Henry's Law constant may be a more appropriate constant outside of the free product zone, where the product is likely to exist in solution with pore water. VOC's with K_H above 0.01 are suitably volatile for removal by soil vapor extraction. Gasoline, with a $K_H = 32$ is particularly well-suited to soil vapor extraction. K_H may also be expressed as a function of the VOC vapor pressure, the concentration of the VOC in water, and temperature as (Daniel 1993):

$$K_H = 16.04 p_a M_a / T C_L$$

where M_a is the gram molecular weight of the VOC, T is the temperature (in Kelvin), and the other parameters are as previously defined. Typical values for hydrocarbons are listed in Table 2.2.

2.3.2 Soil Sorption

Sorption of VOC's to soil particles and organic matter controls the distribution of released products on the soil zone and has a very strong effect on the movement of the VOC through the vadose zone. Sorption onto soil particles from soil vapor can be described as a two-step linear process. VOC vapor will partition from the vapor phase into the liquid water phase. Once in the water, some of the VOC will be adsorbed onto the soil mineral and organic matter. At equilibrium, the degree of partitioning is expressed as:

$$K_D = S/C_L$$

where K_D is the distribution coefficient, S is the mass of chemical adsorbed per unit dry mass of soil solids, and C_L is the concentration of the chemical in the soil moisture. K_D can be determined by conducting a batch adsorption test in which a known mass of soil is mixed with a specific concentration of contaminant and the mass sorbed is measured. A strong relationship exists between the organic content of the soil and the sorption coefficient. As soil organic carbon content increases, the sorption for most products increases. It has also been determined that the particle size of the mineral fraction can have an effect on the distribution coefficient with a sand sized particle having a distribution coefficient about 100 times less than silt and clay sized particles (Daniel 1993).

2.3.3 Weathering and Biodegradation

Weathering refers to the changes in the nature of a chemical mixture after its release into the environment. The compounds composition will change over time and affect the ease with which that product may be removed by soil vapor extraction. The more volatile, soluble, and degradable compounds will be removed from the mixture first, leaving the resultant mixture relatively rich in less-volatile compounds. Table 2.2 shows the effect weathering has on the vapor pressure for gasoline. The decreased volatilization due to the lower vapor pressure will significantly retard the effectiveness of soil vapor extraction. It is well recognized that soil vapor extraction works best on recently contaminated sites.

A natural process which can play a significant role in the remediation of a contaminated soil is biodegradation. Most soils contain microorganisms which if certain basic nutrients exist and an adequate supply of oxygen is available, can biodegrade many fuel hydrocarbons. In the absence of oxygen, degradation of toxic organics can continue due to the ability of organisms to use alternate electron acceptors such as nitrate, sulfate, iron and magnesium oxides and carbon dioxide in place of oxygen. Technologies are being developed which feed oxygen to microorganisms in an effort to enhance biodegradation. Bioventing, which will be discussed in more detail in Chapter Four, is one such method. Although it is presently difficult to predict what part of vapor extraction is due to volatilization and what part to biodegradation, it is important to know which processes are active and to recognize the mechanisms that drive these processes. Enhancing biodegradation allows for more rapid remediation and has the potential for significant cost saving.

Table 2.2 Chemical Properties of Hydrocarbon Constituents (Curtis 1990)

Chemical Class	Representative Chemical	Liquid Density (g/cm ³) @20°C	Henry's Law Constant (dim)	Water Solubility (mg/L) @25°C	Pure Vapor Pressure @20°C	Vapor Density (g/m ³) @20°C	Soil Sorption (KD) (L/kg) @25°C
<u>n-Alkanes</u>							
C4	n-Butane	0.579	25.22	61.1	1560	4960	250
C5	n-Pentane	0.626	29.77	41.2	424	1670	320
C6	n-Hexane	0.659	36.61	12.5	121	570	600
C7	n-Heptane	0.684	44.60	2.68	35.6	195	1300
C8	n-Octane	0.703	52.00	0.66	10.5	65.6	2600
C9	n-Nonane	0.718	NA	0.122	3.2	22.4	5800
C10	n-Decane	0.730	NA	0.022	0.95	7.4	1300
<u>Mono-aromatics</u>							
C6	Benzene	0.885	0.11	1780	75.2	321	38
C7	Toluene	0.867	0.13	515	21.8	110	90
C8	m-Xylene	0.864	0.12	162	6.16	35.8	220
C8	Ethylbenzene	0.867	0.14	167	7.08	41.1	210
C9	1,3,5-Trimethylbenzene	0.865	0.09	72.6	1.73	11.4	390
C10	1,4-Diethylbenzene	0.862	0.19	15	0.697	5.12	1100
<u>Phenols</u>							
Phenol	Phenol	1.058	0.038	82000	0.529	2.72	110
C1-phenols	m-Cresol	1.027	0.044	23500	0.15	0.89	8.4
C2-phenols	2,4-Dimethylphenol	0.965	0.048	1600	0.058	0.39	NA
C3-phenols	2,4,6-Trimethylphenol	NA	NA	NA	0.012	0.09	NA
C4-phenols	m-Ethylphenol	1.037	NA	NA	0.08	0.53	NA
Indanol	Indanol	NA	NA	NA	0.014	0.1	NA
<u>Di-aromatic</u>	Naphthalene	1.025	NA	30	0.053	0.37	690

gasoline 253

weathered gasoline 39

Note: NA - Not available

2.4 Site Characterization

When characterizing a contaminated site for possible remediation by soil vapor extraction, three basic steps are necessary in conducting a thorough investigation. The first is a preliminary screening of the area in order to map the zone of contamination. This should include identifying the source, emergency response and abatement if necessary and the use of various probing techniques to accurately identify the area and concentration of contaminant. The second step is to develop a comprehensive picture of the subsurface conditions. This includes soil types, stratigraphy, water table level and any other pertinent information necessary to accurately show the site geology and hydrogeology. The final step in site characterization is to test certain technology-specific parameters that are necessary to determine if soil vapor extraction is feasible. These include air permeability testing to determine vapor flow rates through the soil zone and ground water pumping tests to determine the drawdown capability of the water table.

2.4.1 Preliminary Site Screening

Soil vapor extraction is used above the water table in the unsaturated area known as the vadose zone. The vadose zone is defined as the hydrogeologic profile extending from the ground surface to the upper surface of the water table. It is broken down into three separate zones; the soil zone, intermediate vadose zone and the capillary fringe. The soil zone is the upper layer where chemical and physical weathering are the highest. The intermediate vadose zone is the unweathered transition layer below the soil zone. The capillary fringe is the zone which extends from the base of the unsaturated zone down to the water table. It is defined as a water laden area with negative water pressures which rises through soil pores due to surface tension.

Defining the capillary fringe and its location is extremely important in an investigation of a contaminated zone for a petroleum hydrocarbon because it can act as a barrier to the free product light non-aqueous phase liquid (LNAPL).

To be able to accurately map the zone of contamination, one must understand how the free liquid travels in the vadose zone. Figure 2.3 shows the movement of an LNAPL plume down to the water table. Notice that the contaminant does not move into the water table zone. Instead it "pancakes" and forms a pool of free liquid. As discussed previously, during the movement downward, the contaminant is volatilizing

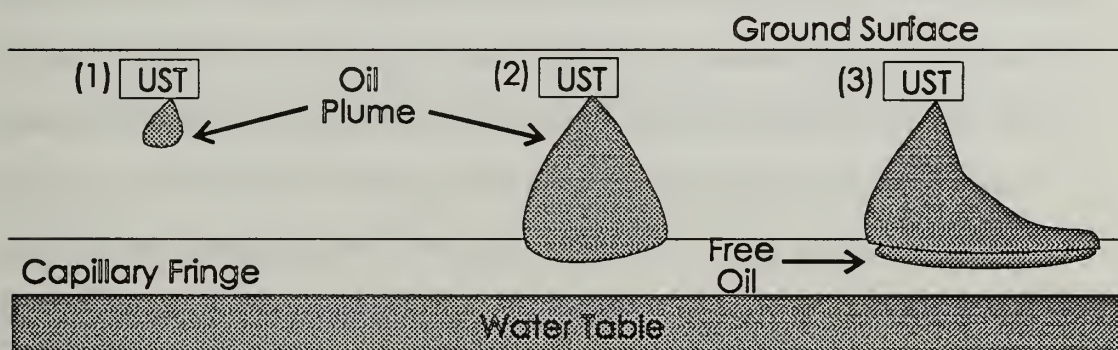


Fig. 2.3 Three stages of contaminant distribution in a sandy hydrogeologic system.

into soil vapor, mixing with soil moisture and being adsorbed by soil particles creating an area of contamination extending from the source down to the water table.

Additionally, as the water table rises and falls, the vadose zone is continually reexposed to the contaminant, even if the source has been eliminated. This is not to suggest that the water table acts as a complete barrier to contaminant movement. In the case of gasoline, components such as benzene will dissolve into the water at low concentrations and create a separate plume of contaminated water.

Another problem that makes remediation of hydrocarbons difficult is the formation of ganglia. Ganglia are bubbles of NAPL that form in soil pores as shown in Figure 2.4. One of the reasons flushing is not typically a successful remediation technique is that the ganglia are held in place by capillary action similar to air bubbles. (Figure 2.5). In Chapter Three and Four, several methods for dealing with this problem will be discussed.

With a basic understanding of how the contaminant moves, the zone of contamination can be tracked. The first step is to attempt to determine the source of contamination. It may be an underground storage tank, leaking pipelines, or intentional or accidental spills which have caused the contamination. For obvious reasons, the source needs to be identified and eliminated. Emergency response and abatement may be necessary to assess the immediate impact on potential human and environmental receptors. This process is conducted in a relatively short period of time (days). It is not always a simple matter identifying the source and in some cases, it may be impossible.

Examining historical records and interviewing site personnel can often help in tracking down the source. Soil gas surveys can be a valuable tool in determining the location and extent of soil and groundwater contamination. As discussed previously, VOC's volatilize from free liquid and soil moisture and move upward and vent at the surface. This movement through the soil pores results in detection up to 50-75 yards from the source. Through this technique, contaminated soil can be identified and its concentration calculated. With this information, a concentration contour map can be established. In order to accurately conduct a soil vapor survey, factors such as size and age of the source, moisture content and organic carbon content of the unsaturated zone, and the volatility and solubility of the VOC should be known.

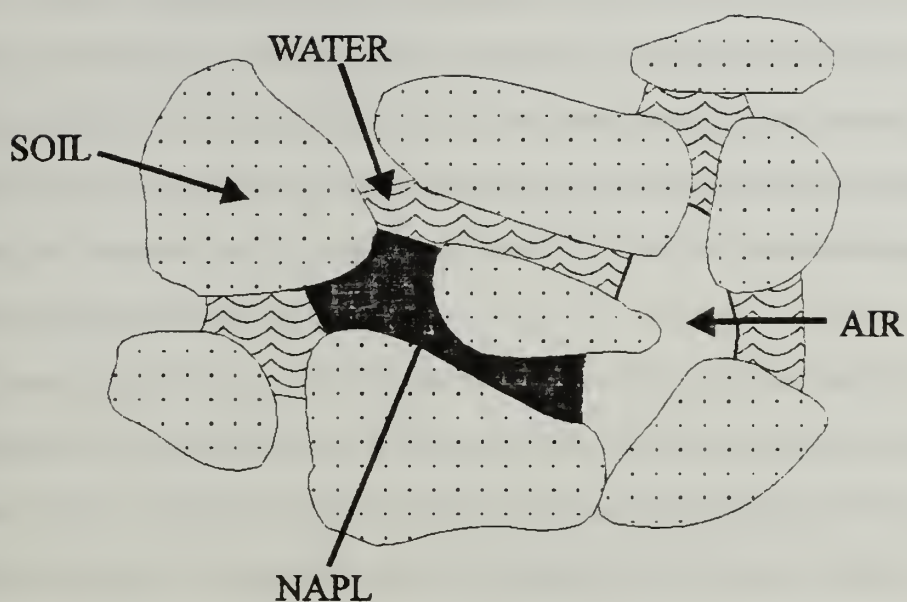


Fig. 2.4 Four phases of a contaminated unsaturated zone

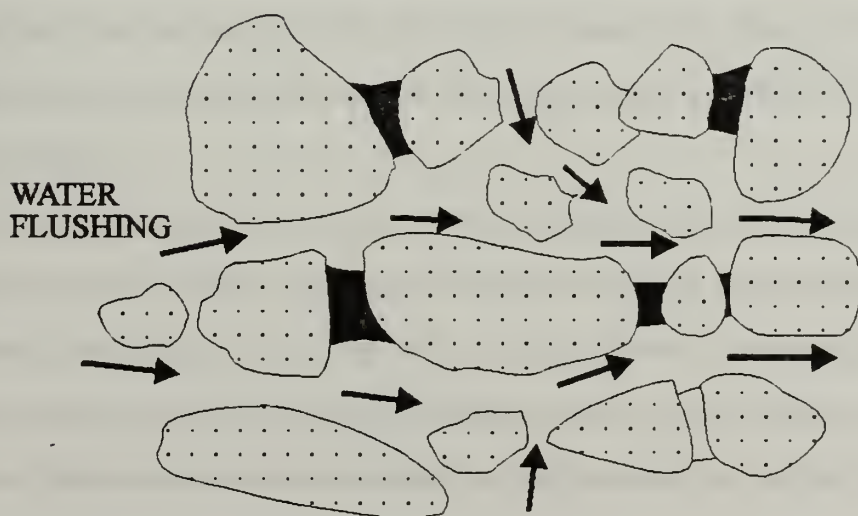


Fig. 2.5 Residual contaminant form remedial flushing

Several sampling methods are available to perform the soil vapor survey. These include grab sampling of soil cores, flux chambers, accumulator devices and suction probes. The advent of the portable field gas chromatograph (GC) has made field identification of contaminated zones possible, allowing field personnel to quickly determine concentrations at an individual location. Several of these techniques use this new technology to their advantage.

-Grab sampling of soil cores: This method involves taking a soil core sample, sealing the sample and using laboratory GC analysis of the headspace to detect contaminant vapors. This is a relatively simple technique using standard coring procedures; however, the vapor concentration can be compromised by improper handling and the turnaround time from the laboratory makes it ineffective for most site investigations.

-Flux Chambers: In this method, a chamber is placed on the ground. Clean dry air is added to a chamber at a known rate. The exit air is analyzed with a field GC to determine vapor content. This technique can be performed on the surface or by using a downhole method. The advantage of this technique is that it allows for quick analysis in the field. The disadvantage is that diluting the chamber with clean air reduces its detection limits. The downhole method has a better detection limit but it is much more labor intensive.

-Accumulator Method: This method involves the passive capture of soil gas onto an adsorbent contained within a glass tube. This trap is placed in the ground just below the surface and can be left for several hours or up to 30 days. The adsorbent is a metal wire coated with charcoal. Following completion of the exposure period, the device is sent to a lab and the charcoal is analyzed for VOC content. This method provides an accurate determination of the gas flux and the sensitivities can be adjusted by the

exposure time. The disadvantages are it can only be used for shallow depths, vertical profiling is not possible, the results can be affected by outside VOC sources, i.e. air emissions, and possible concentration losses from the charcoal over time.

-Suction Probes: This method involves inserting a tube into the ground, placing a vacuum on the tube to draw a soil vapor sample and using a field GC to analyze the vapor concentration. This technique is by far the best technique for preliminary site evaluations and contaminant mapping. Advantages of this system include on-site evaluation of results which allows field personnel to vary sampling locations as necessary. Sampling depths can be varied in order to accurately profile the site. Probes can be driven by hand up to about three feet. Up to 20 feet, hydraulically pressed probes can be used. Below 20 feet, hollow stem augers are used with the probe driven ahead. Sampling can also be done below pavement. Disadvantages of this technique are that it can be very labor intensive and it is not well suited to finer grained, clayey soils.

An important aspect of any soil vapor survey is the grid spacing used when investigating the site. Under ideal dry conditions with a coarse-grained soil, soil gas would be expected to diffuse away from the source to a distance equal to the thickness of the unsaturated zone. This diffusion is significantly affected by the soil moisture content as well as the grain size. Soil moisture in the pores will act as a barrier to vapor transport. Fine-grained soils will tend to have a higher capillary fringe thus reducing the unsaturated zone and limiting vapor movement. Soil heterogeneities, organic content, which is typically higher in clayey soils, as well as the age of the VOC will also limit vapor movement. It is suggested that for a large site, 3-5 times the depth to the water table or 50-100 feet be used as the grid spacing. Under dry soil

conditions, 100 feet may be sufficient to detect contaminant, however under wet soil conditions, grid spacing may be limited to 30 feet or less. This is one of the main advantages of the suction probe technique, which allows an experienced technician to assess the field conditions and adjust the spacing accordingly. Figure 2.6 shows a typical grid spacing used in a site investigation with a technique for mapping the contaminant zone called halving. A typical grid is set up and samples are taken. As contaminated areas are discovered the grid is split in half between holes in order to more accurately map the

contaminant. At each location, a typical probing technique would be to drive the probe a specific depth, take a sample and then drive the probe deeper. This technique will provide both a lateral sketch of the contaminant concentration and a vertical profile. With the site investigation complete, a map of the site can be established. An example of this is shown in Figure 2.7. The concentration levels are shown as contour lines on the site plan. The vertical profile can also be plotted to give an accurate picture of the entire site. This type of plot would not be complete until soil boring were taken and exact contaminant concentration were established. However, using the preliminary information from the soil gas survey will enable the investigator to select boring locations, thus reducing the number of soil borings required at a site.

The cone penetrometer, which is essentially an instrumented steel rod that is driven into the soil, is becoming a popular tool for preliminary site screening investigations. By measuring the shear and normal forces on the leading end of the rod, soil structure can be preliminarily defined and the hydraulic conductivity can be roughly estimated. Some cone penetrometers are also constructed to allow the collection of vapor or ground water samples. It should be emphasized that the results

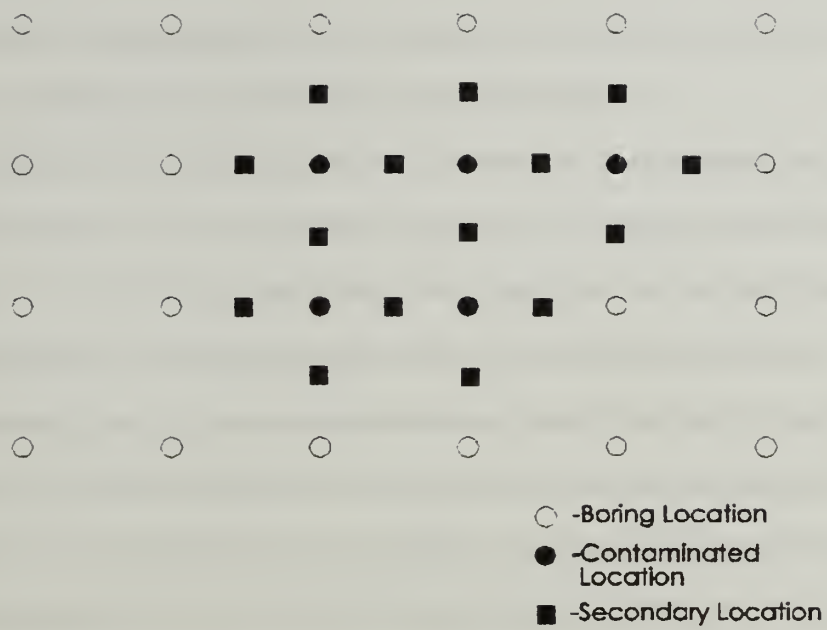


Fig. 2.6 Grid spacing diagram

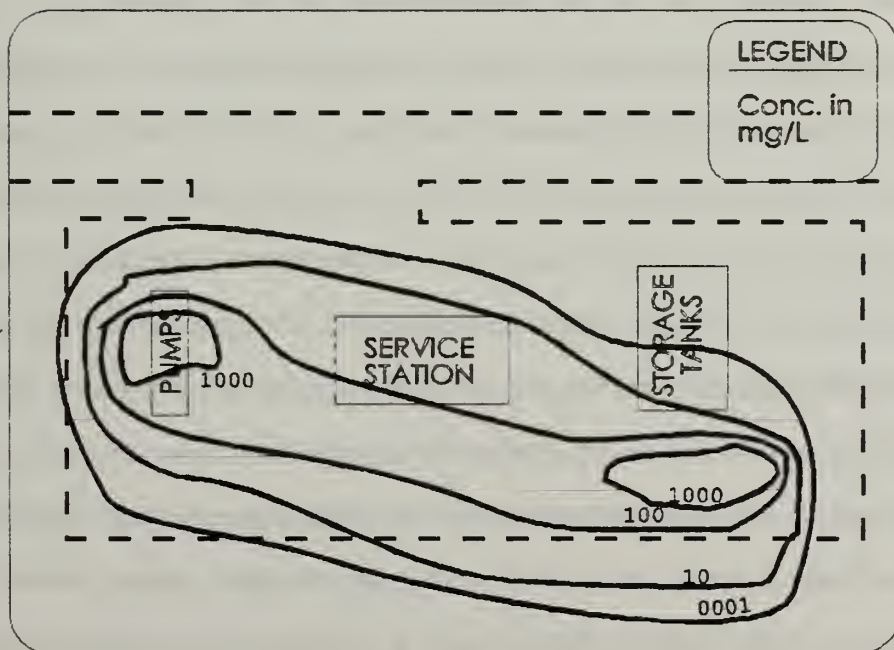


Fig 2.7 Contaminated Site Map.

obtained from a cone penetrometer are at best rough estimations and should not be used as a quantitative analysis of environmental parameters.

A problem that exists with any soil vapor survey is establishing the true contaminant source. In a heavily industrialized site with multiple contamination sources, it can be difficult to determine if the extracted vapors are from the source being investigated. This is particularly true when investigating groundwater contamination where the relative concentration of contaminant vapors may be fairly low and can be easily masked by other sources such as surface contaminants. The field GC will be able to discriminate between different compounds. However if there are several contaminated zones with similar chemical characteristics, this may not be possible. In this case, more advance laboratory GC analysis may be necessary to distinguish sources.

2.4.2 Detailed Site Characterization

This portion of the site characterization mirrors many types of geotechnical site investigations for engineering projects. In order to determine if a specific remediation technology is feasible, the site must be well characterized. The soil environment significantly affects the transport of VOC's and the likelihood of success with soil vapor extraction. This investigation must analyze the soil on the microscopic level as well as the macroscopic level. Soil properties that are important include the soil porosity, which will give information on the ease with which vapor transport will occur. Moisture content is an extremely important parameter of the soil and can significantly affect the applicability of vapor extraction. High water content reduces the air-filled porosity and limits vapor flow. If the water content is very low, however, sorption by soil particles increases, leading to reduced volatilization into a soil gas. A

range of 94 to 98.5 percent relative humidity in soil gas is considered to be the optimum for soil vapor extraction. Concern over water content requires that the water table level and the height of the capillary fringe be accurately established. Any free LNAPL will tend to pool at this level while moisture from the capillary fringe will tend to impede vapor transport. Other factors such as soil type and structure, and grain size distribution, are also important parameters which should be determined.

Heterogeneity influences vapor movement as well as the soil structure and can affect remediation quality. Significant differences in air conductivity may exist in different soil layers, possibly making soil vapor extraction more or less difficult. A horizontally stratified soil may be favorable. Relatively impervious strata will limit the rate of vertical inflow from the surface and make the vacuum more effective horizontally from the extraction point. Accurate placement of extraction well screens can optimize this layering effect and reduce remediation time. This heterogeneity can also impair soil vapor extraction. Contaminated, low permeable soils will have to rely on diffusion as the mechanism for vapor transport, which will greatly increase remediation time. Similarly, dead end areas in the soil structure will not allow air to flow through them and will release contaminants by diffusion, as well. Thus it is important to know the soil properties and well as the variation in the soil profile.

The primary means for determining these site characteristics is through soil borings. These same methods are used on most geotechnical investigations and groundwater development studies and are readily available. Use of the mapped zone of contamination offers an excellent means for determining soil boring locations; however, it is important to have a complete site picture and boring should not be limited to high concentration areas. Certain geophysical methods can also provide

important information about water table and bedrock locations as well as soil characteristics in the borehole and may be advantageous in certain situations.

One of the major concerns with any soil exploration of a contaminated site is cross-contamination. This is typically not a major concern on most geotechnical site investigations and testing firms may not understand the importance of proper drilling procedures which limit this problem. A technique which is used to limit downhole contamination is to drill to a depth slightly greater than the contaminated zone, set a casing and then continue drilling with a smaller diameter auger. Equipment should also be cleaned between borings in order to eliminate carrying contaminants from hole to hole. It is the engineers responsibility to recognize these potential problems and ensure that improper drilling techniques don't compromise test results.

2.4.3 Technology Specific Testing

The air permeability of the soil is probably the single most important soil parameter with respect to the success of soil vapor extraction. The permeability incorporates the effects of several soil and vapor characteristics. These include porosity, grain size distribution, and water content of the soil as well as vapor viscosity and density. All things being equal, soil vapor extraction applicability is a function of air permeability.

Darcy's law governs the flow of fluid through a porous media. The equation for one-dimensional flow is:

$$Q=kiA$$

where Q is the flow rate (L^3/T) through a porous medium with a cross-sectional area A (L^2), k is the hydraulic conductivity (L/T), and i ($= \Delta h/L$) is the gradient of head loss between any two points. The coefficient of permeability is a function of the

porous medium matrix and the properties of the fluid. The intrinsic permeability, K , represents the ability of the medium to conduct flow and is a true characteristic of the soil and is related to the coefficient of permeability by the following equation:

$$k = Kpg/\mu$$

where p and μ are the density and the dynamic viscosity of the fluid, and g is the force of gravity. It is possible to estimate the coefficient of permeability to air directly from the hydraulic conductivity of water. The relationship is represented by the following equation:

$$k_a = Kp_a g/\mu_a = k_w \mu_w p_a / p_w \mu_a$$

This approach provides an estimate of the coefficient of permeability of air. However, field permeability tests should be performed in order to obtain a more accurate estimate of the field permeability. Fissures, macropores, and cracks may affect the air flow at the site and these features would not be adequately represented in a typical hydraulic conductivity test.

Field air permeability tests are performed using a series of monitoring wells spaced around the site. The testing is conducted by hooking the vacuum side of an extraction blower to a well head and measuring the vacuum created at the wellheads of surrounding wells over a period of time. The testing period should be long enough to achieve steady-state conditions. This procedure is repeated on surrounding wells in order to isolate low permeability areas. The air permeability k is calculated by the following formula (Johnson 1990):

$$P' = Q/(4\pi m(k/\mu))[-0.5772 - \ln(r^2 e \mu / 4kP_a) + \ln(t)]$$

P' = gauge pressure measured at distance r and time t ; m = stratum thickness; r = radial distance from the pumping wells; μ = viscosity of air; e = air-filled soil void fraction;

t = time; Q = volumetric vapor flow rate from the pumping well; and P_a = ambient atmospheric pressure. The equation above predicts a plot of P' vs. $\ln(t)$ which should be a straight line with slope A and y-intercept B equal to:

$$A = Q/4\eta m(k/\mu)$$

$$B = Q/4\eta m(k/\mu)[-0.5772 - \ln(r^2 e \mu / 4kP_a)]$$

If both Q and m are known, the equation for A can be used. If Q and m are not known then values of A and B are both used in the following equation:

$$k = (r^2 e \mu / 4P_a) \exp(B/A + 0.5772)$$

Vapor samples should be taken at the beginning and end of the test, which should be conducted long enough to extract one pore volume, V_p , of vapor. This ensures that all vapors existing in the formation prior to venting are removed. The vapor concentration at the start of the test is representative of the equilibrium vapor concentration, while the concentration measured after one pore volume is removed represents realistic removal rates. The time t_p for one pore volume to be removed is:

$$t_p = V_p / Q = e \pi R^2 H / Q$$

where R , H , e , and Q are the radius of the zone of contamination, vertical thickness of the zone of contamination, air-filled void fraction, and volumetric vapor flow rate from the extraction well. Analytical and numerical air flow models are also available which will simulate soil conditions to calculate design parameters for soil vapor extraction systems as well as using field air pump data to solve for air permeability.

A second test that should be performed during the site characterization phase of a project is the ground water pumping test. To achieve efficient venting, the contaminated soil has to be exposed to air flow, which in turn requires that the water table be lowered to counter-act the upwelling effect caused by decreased vapor

pressure near the extract well. The ground water pumping system needs to have a sufficient pumping rate and be operated for a long enough time period to obtain the required drawdowns. Two water table parameters are needed for the design; average transmissivity T and the storage coefficient S . These parameters can be estimated using the results of the standard transient ground water pumping test with a constant pumping rate (Bear 1979). Using the estimated values, the required pumping rate may be calculated as follows:

$$A = 4\pi TS(r,t)/W(u)$$

where $W(u)$ is the well function (Bear 1979) of $u = Sr^2/4Tt$, and $s(r,t)$ is the required drawdown at distance r and pumping time equal to t .

3.0 Components & Design Parameters of Vapor Extraction Systems

3.1 Introduction

When designed and operated properly, soil vapor extraction systems can be cost-effective in removing a variety of volatile organic chemicals over a wide range of conditions. The design and operation of these systems is flexible in nature. This flexibility is necessary not only because of variability at each site but also because changes in the nature of the contaminant as components volatilize require that the systems be able to adapt in order to effectively remove the contaminant over the life of the project. Some of these parameters include rates of air withdrawal, the configuration of the wells and their spacing, how and where inlet venting is applied, surface ground cover as well as pumping duration. Higher air flow rates tend to increase vapor removal because the zone of influence is increased and air is forced through more of the air-filled pores. More wells will allow better control of air flow but will also increase the construction and operations cost. Intermittent pumping allows time for diffusion and can actually increase removal rates. Each of these parameters must be evaluated during the design and pilot study period and then must be reevaluated during the operation of the system in order to optimize results.

A basic system such as the one shown in Figure 3.1, combines extraction wells with vacuum pumps to remove vapors from the vadose zone and reduce contaminant levels. The components of soil vapor extraction systems are typically off-the-shelf items, and the installation of wells and trenches can be done by most environmental firms. However, the design, operation, and monitoring of soil vapor extraction systems is by no means a simple matter. Choosing if venting will even work at a specific

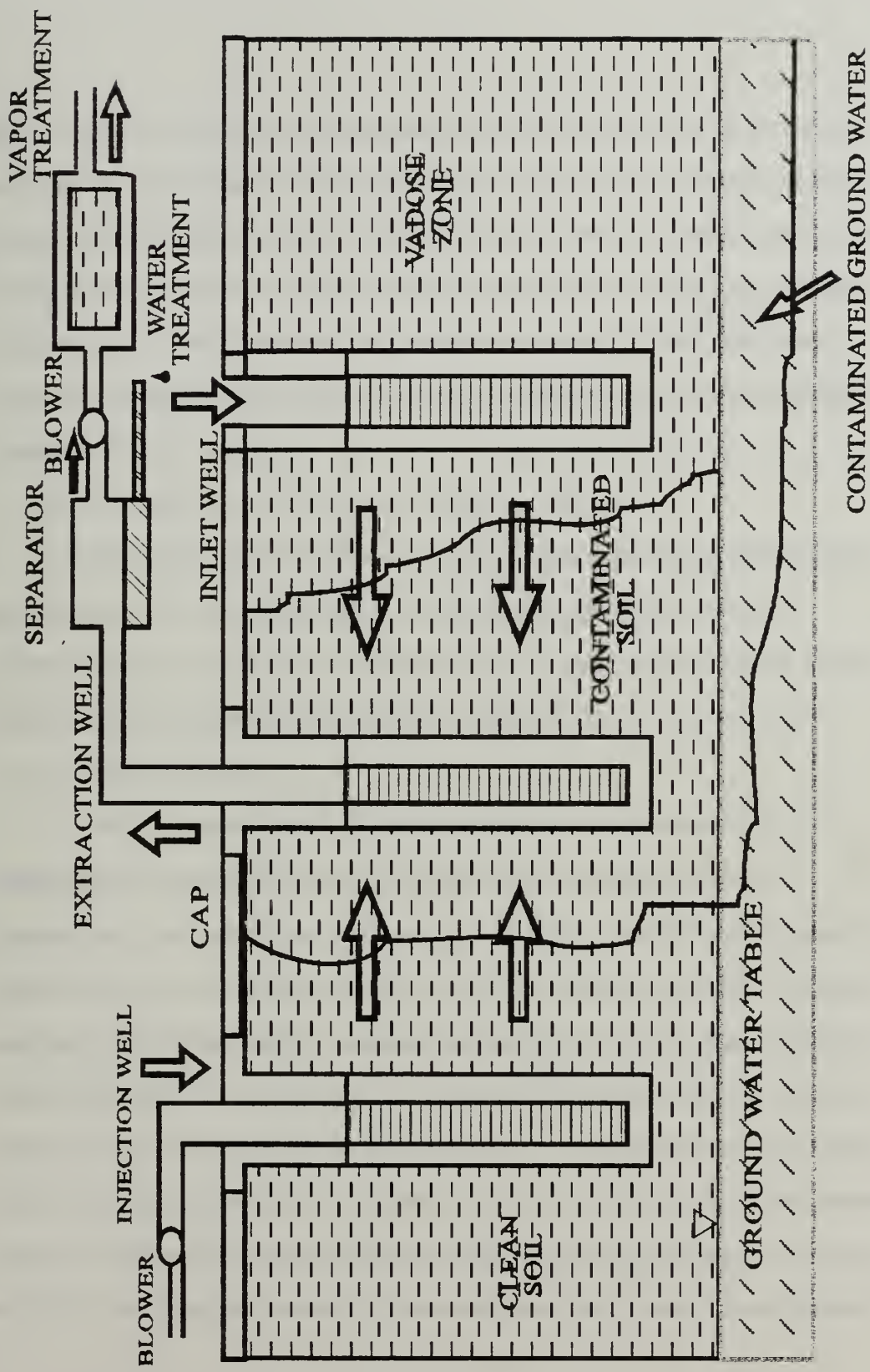


FIG. 3.1 TYPICAL SOIL VAPOR EXTRACTION SYSTEM

site can be very difficult. This chapter will first provide an overview of the components which are typically a part of the vapor extraction system as well as optional equipment used to enhance design features. Following this discussion, a systematic approach will be presented to decide if soil vapor extraction is applicable at a given site and design decisions required for an efficient and cost-effective system. Finally, pitfalls and concerns of vapor extraction systems will be discussed to provide insight into possible limitation of this technology.

3.2 Components of a Soil Vapor Extraction System

Before a discussion on the design of a soil vapor extraction system can begin, the components of the system and their function within the system must be understood. A typical soil vapor extraction system includes extraction wells, air inlet wells, blowers, and vapor treatment shown in Figure 3.1.

3.2.1 Extraction wells

Wells are installed within the contaminated area for the recovery of contaminants. Generally, pilot testing is performed and combined with soil characteristics data to determine well spacing and depths. The radius of influence of a single extraction well can range from 10 to 100 feet. Typically, extraction wells are designed to fully penetrate the unsaturated soil zone to be cleaned. The techniques used to construct extraction wells are the same used for most monitoring wells. An example is shown in Figure 3.2. Extraction wells are typically constructed of slotted plastic or steel pipe, 2-4 inches in diameter. PVC plastic pipe is the preferred material because of its lower cost and availability; however, certain volatile organics can react with PVC and soften the material. When remediating these types of contaminants, it

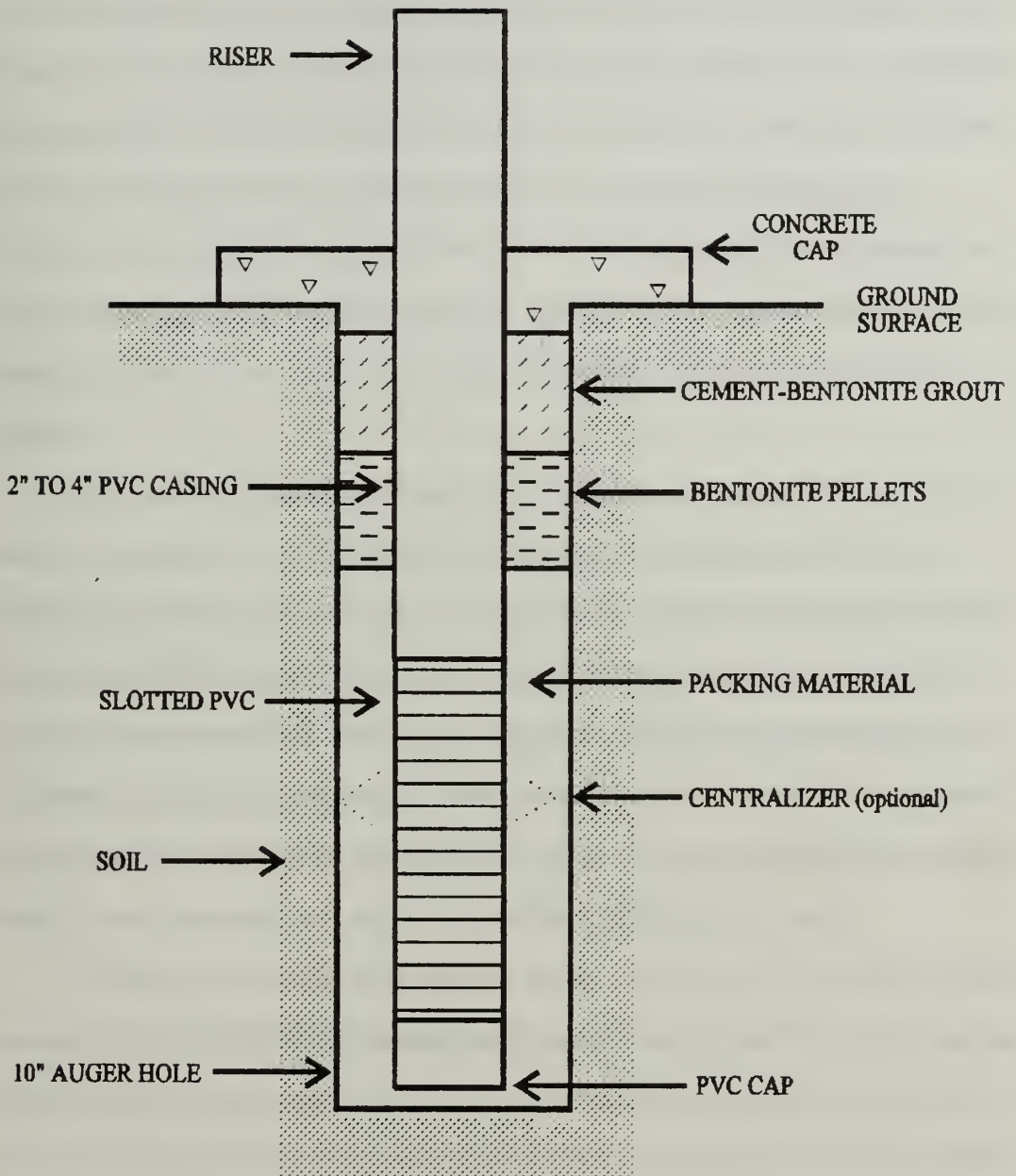


FIG. 3.2 Typical extraction/air inlet well construction

may be necessary to use steel piping, especially if the piping will be exposed to high concentrations for long periods of time. The well screen is placed in a permeable filter packing similar to water production wells in order to maintain a free flow of air into the well. The length of the well screen open to the contaminated area plays a significant role in the performance of the system. Having the well screen above the contaminated zone will increase the air flow through the uncontaminated zone. Larger boring sizes are also preferred because they provide air/water separation in the packing.

An important feature of the well is the bentonite seal placed above the filter pack. If a proper seal is not made around the piping, the system could be short-circuited by air flow down the pipe which will reduce removal rates. Bentonite pellets are a standard sealant material because of their swelling capacity when exposed to water and low permeability. Wells may be aligned vertically or horizontally. Vertical alignment is used for deeper contamination zones and results in radial flow patterns. If the depth of the contaminated soil is less than 10 to 15 feet, it may be more practical to dig a trench across the area and install perforated piping in the trench.

Usually several wells are installed at the site, particularly if the soil has variable permeability. In stratified soils, several wells may be placed at each location at varying depths to allow venting of each strata. The well head connections at the top of the well, which connect to the common manifold, can be cast in concrete vaults at grade with traffic rated covers or above grade when not in the way of traffic.

3.2.2 Air Input Wells

In a simple vapor extraction system as shown in Figure 3.3, the air flow paths from the surface to the extraction well are uncontrolled. The air flow will typically

take the path of least resistance through the soil stratum which may not pass effectively through the zone of contamination. To maximize air flow in these zones , it may be necessary to install air inlet wells. Air inlet wells come in two types; air vents which are passive and allow a free flow of air from the ground surface to the extraction well and injection wells which forces air into the ground and toward the extraction wells. Injection wells are also installed between extraction wells to ensure pressure gradients in the direction of the extraction well. Typically, injection wells and air vents are constructed in a similar fashion to extraction wells. Sometimes, extraction wells and inlets wells are designed with the same features in order to allow more flexibility in the patterns of extraction at the site. This procedure can significantly increase construction costs and is typically only used at highly stratified sites. Heaters can be installed to increase the injected air temperature and enhance volatilization of the contaminant. As with extraction wells, well spacing and depths usually are determined from pilot testing and soil characteristics. In most cases, only a small part of the extracted air comes from the air inlet which indicates that the surface is still the primary source of non-contaminated air (Hutzler 1989).

3.2.3 Covers

If controlling the flow of air at the site is a critical factor in the effectiveness of the extraction system, a impermeable cap may be placed on the surface. This can be done with plastic sheeting, clay, concrete, or asphalt pavement. The cover will tend to make the air move in a radial rather than a vertical pattern. This is demonstrated in Figure 3.3 and 3.4. The cover will also control the air flow pathway so that clean air is more likely to come from the air inlets wells. Covers may also be necessary if the infiltration of water is a concern. Infiltration will increase the moisture content which

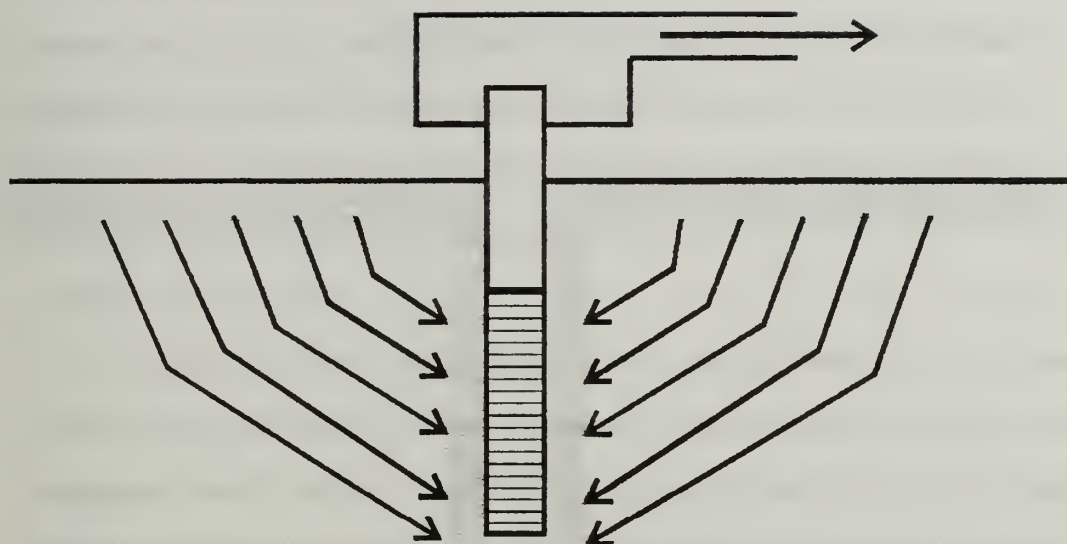


FIGURE 3.3 AIR FLOW PATTERNS IN VICINITY OF A SINGLE EXTRACTION WELL – NO CAP

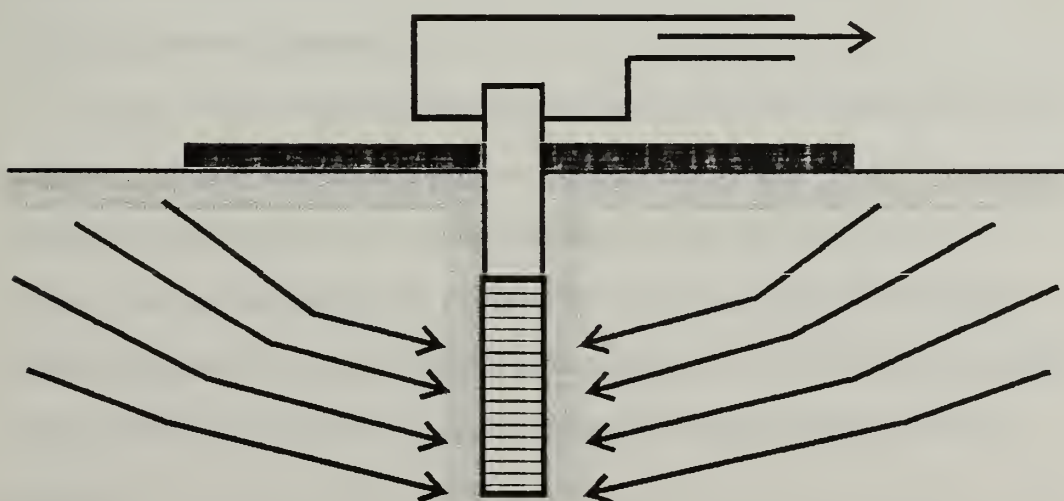


FIGURE 3.4 AIR FLOW PATTERNS WITH IMPERMEABLE CAP

can restrict air flow. Additionally, limiting infiltration will reduce the amount of water drawn into the extraction well and possibly eliminate the need for an air/water separator. Care should be taken when limiting the moisture content of the soil. Extremely dry conditions may reduce the efficiency of the extraction system by increasing the adsorption capacity of the dry soil.

3.2.4 Vacuum Source

Typically, standard positive displacement industrial blowers, rotary blowers, vacuum pumps, or turbines are used for extracting soil air. There are a large number of commercial models available for producing a vacuum. Blowers are typically rated from 100 to 6000 cubic feet per minute at vacuums up to 30 inched Hg gauge. Electric motors rated from one to ten horsepower are standard. Due to the volatile nature of constituents, explosive proof motors should always be specified and in populated areas, noise suppression may be required. Outlet pressure from the blowers is normally used to push the air flow through the treatment system and is sometimes used as the source for the injection wells.

3.2.5 Air/Water Separator

If water is removed from the extraction wells, an air/water separator will be necessary to protect mechanical equipment and increase efficiency of the treatment system. Any condensate removed will more than likely have to be treated as a hazardous waste depending on the contaminant level. As stated previously, the air/water separator may be eliminated if an impermeable cover can limit the moisture content of the soil. In some cases, separators may be used for product recovery purposes.

3.2.6 Vapor Treatment

Treatment of emissions from the vapor extraction process may or may not be required, depending on the constituent characteristics, emission rates, cost-effectiveness, and air emission regulations. Numerous treatment systems are available including liquid/vapor condensers, incinerators, catalytic converters, and gas phase granular activated carbon (GAC). GAC units are the most common if product recovery is not important, however as the amount of water increases, the carbon replacement rate increases. This carbon may be considered a hazardous waste and would have to be disposed of accordingly. If the extraction rates are high, i.e. several hundred pounds per day, incineration may be more feasible. This can be accomplished by self-sustained combustion if the concentrations are high in hydrocarbons and are combustible, or by supplementing with auxiliary fuels.

3.2.7 Miscellaneous Components

Various additional equipment will be required for a soil vapor extraction system including control/shut-off valving, gas flow meters, sampling ports, pressure gauges, constituent analyzers as well as vapor and pressure monitoring probes around the site.

3.3 Design Parameters for Soil Vapor Extraction Systems

Vapor extraction is a fairly straightforward remediation technique. By applying a vacuum to a contaminated unsaturated zone, volatilization of the contaminant is induced and the vapors are removed and treated or incinerated. Design of such systems has typically been accomplished more by experience than through a logical design "process." Typically, field tests and pilot studies are used to determine if soil

vapor extraction is applicable and to ascertain parameters necessary for designing the system. As a more logical approach, Johnson (1990) developed a decision tree (Figure 3.5) and a series of questions which can be used as a road map in making decisions on whether soil vapor extraction is applicable and if so, the steps necessary in designing a cost-effective system. Many of the steps addressed in this decision tree were discussed in Chapter Two on contaminant and site characterization and will not be discussed in detail here.

3.3.1 Is Soil Vapor Extraction Appropriate?

The major factors which govern the effective application of soil vapor extraction technology are the vapor pressure and volatilization of the contaminant i.e. the vapor concentrations and flow rate; and the air permeability or vapor flow path through the contaminated zone. In applying these factors to the decision on whether vapor extraction will work, several questions must be answered:

- 1) What contaminant vapor concentration will be obtained?
- 2) Will this concentration give an acceptable removal rate?
- 3) What range of vapor flow rates can be expected in the field?
- 4) Will the contaminant concentrations and vapor flow rates produce acceptable removal rates?
- 5) What residual constituents will be left in the soil?
- 6) What will be the composite and concentration changes of the contaminant over time?
- 7) Will these values comply with regulatory requirements?

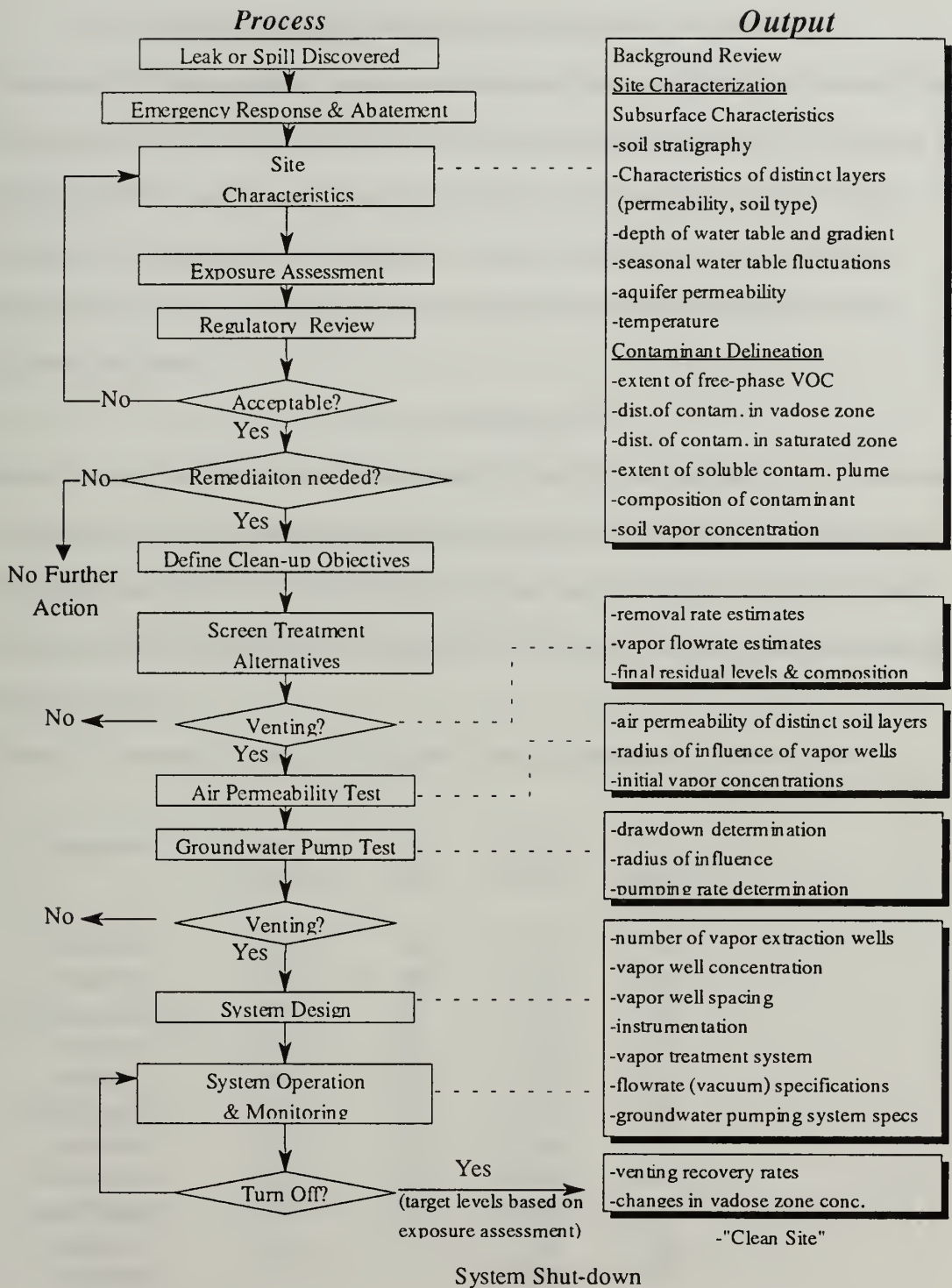


Fig. 3.5 In situ soil-venting system design process (Johnson 1990)

3.3.1.1 What contaminant vapor concentrations will be obtained?

Estimates of the contaminant vapor concentration, C_{est} , can typically be obtained from soil vapor surveys or headspace analysis during site characterization. In the absence of this type of data, vapor concentrations can often be estimated for certain common contaminants like gasoline. The maximum vapor concentration of a contaminant, which is known as the saturated vapor concentration, can be calculated from the following equation:

$$C_{est} = \sum x_i P_i M_{w,i} / RT$$

where x_i is the mole fraction of component i in liquid phase residual ($x_i = 1$ for a single compound), P_i is the pure component vapor pressure at temperature T (atm), $M_{w,i}$ is the molecular weight of i (mg/mole), R is the gas constant (0.0821 atm/mol K), and T is the absolute temperature of the residual (K). Values of C_{est} for typical contaminants are shown below:

Table 3.1 Selected Compounds and Their Chemical Properties (Johnson 1988)

Compound	M_w (g/mole)	T (C)	P_v 20 C (atm)	C_{est} (mg/L)
n-pentane	72.2	36	0.57	1700
n-hexane	86.2	69	0.16	560
trichhloroethylene	131.5	87	0.026	140
benzene	78.1	80	0.10	320
toluene	92.1	111	0.029	110
chlorobenzene	113	132	0.012	55
p-xylene	106.2	138	0.0086	37
ethylbenzene	106.2	138	0.0092	40
napthalene	128.2	218	0.00014	0.73
gasoline	95	-	0.34	1300
weathered gasoline	111	-	0.049	220

It should be noted that the vapor concentrations calculated in the equation above are estimates at the beginning the operation. Contaminant concentration in the vapor removed will be highest in the beginning of the operation and will drop off considerably as vapor extraction continues. This is due to changes in the composition of the contaminant and increased diffusion resistance.

3.3.1.2 Will this concentration give an acceptable removal rate?

Once the vapor concentration has been estimated, one must determine if an acceptable removal rate can be achieved. This is accomplished by multiplying the concentration estimate C_{est} by a range of reasonable flow rates, Q :

$$R_{est} = C_{est} Q$$

Typical flow rate reported (Hutzler et al. 1988) for extraction operations at service station ranged from 10 - 100 scfm (Hutzler et al. 1988) although for sandy soils or large numbers of extraction wells, flow rates as high as 100 - 1000 scfm are achievable (Johnson et al. 1990).

At this point, the engineer must decide what is an acceptable removal rate. From the decision tree shown in Figure 3.6, one of the most important steps that must be accomplished during a remediation project is to establish cleanup objectives for the site. One of these objectives will be a estimated time frame for completion of the project. With an estimated project time, acceptable removal rates can be determined by dividing the estimated spill mass M_{spill} by the maximum cleanup time τ :

$$R_{acceptable} = M_{spill} / \tau$$

$R_{acceptable}$ is then compared to R_{est} to determine if vapor extraction is still a viable option. Generally, removal rates < 1 kg/day would be unacceptable for most contaminants, so soils contaminated with compounds having saturated vapor

concentration less than 0.3 mg/l will not be effectively remediated by soil vapor extraction unless the vapor flow rate exceeds 100 scfm. Again it should be noted that at this point, decreases in the vapor concentration due to composition changes and mass transfer resistance have not been taken into account.

3.3.1.3 What range of vapor flow rates can be expected in the field?

So far the discussion has been on theoretical flow and removal rates. In order to determine if vapor extraction is feasible at a particular site, realistic vapor flow rates for the field conditions encountered must be estimated. A method of predicting the flow rate per unit length of the well screen, Q/H , is in the equation shown below:

$$Q/H = [\pi k p_w / \mu] [1 - (P_{Atm}/P_w)^2] / \ln (R_w/R_I)$$

where k is the air permeability (cm^2), μ is the viscosity of air (g/cm-s), P_{Atm} is the absolute ambient pressure (g/cm-s^2), P_w is the absolute pressure at the extraction well (g/cm-s^2), R_w is the radius of the extraction well (cm) and R_I is the radius of influence of the extraction well (cm). This equation is a simple steady state radial flow solution for compressible flow, but does provide reasonable estimates of vapor flow rates. If k can be measured or estimated, then the only unknown in the equation is the radius of influence. As stated in Chapter 2, the radius of influence can range from 10 - 100 feet. Because the equation is not sensitive to large changes in R_I , mid-range values of 40 - 50 feet can be used without a significant loss of accuracy. This is particularly true since the air permeability factor, k , can vary by several orders of magnitude at the site and measuring k to within one order of magnitude is the best possible accuracy which can be reasonably expected.

3.3.1.4 Will the contaminant concentrations and vapor flow rates produce acceptable removal rates?

So far, the removal rates estimated have been the maximum rates possible when the vapor flow is through the contamination zone, no compositional changes occur to the contaminant and there are no mass-transfer limits encountered. This is a best case condition and will not be typically encountered in the field. Conditions such as vapor flow through uncontaminated zone will reduce the removal rates. This is dependent on the fraction of air flow which passes through the uncontaminated zone. Johnson et al. (1988) presented several equations which could be used to predict more realistic removal rates. Due to the detail of this paper, the equation will not be presented. One should consult that paper for more details.

3.3.1.5 What residual constituents will be left in the soil, what will be the composite and concentration changes of the contaminant over time, and will these values comply with regulatory requirements?

It is important to remember that soil vapor extraction has practical limits on the final soil contamination levels achieved. Removal rates at the beginning of an operation will be high and a significant percentage of the contaminant will be removed early on. As contaminants are removed from the soil, the residual contamination level decreases and the composition becomes richer in less volatile compounds. At low residual levels, the equilibrium vapor concentrations are expected to become proportional to the residual soil contaminant concentrations. As vapor extraction continues and residual soil levels decrease, it becomes more and more difficult to remove the last residual contaminant. The changes in composition, vapor concentration, removal rates, and the residual soil contamination level with time are all functions of the initial residual

composition, vapor extraction well flow rates, and the initial soil contamination level. Several models have been developed which analyze these various parameters and develop time related curves which can be used to predict removal rates for a specified vapor flow rate or can estimate vapor flow rate requirements if the removal rate is specified.

As stated previously, there are practical limits on the amount of contaminant that can be removed by vapor extraction. In the case of gasoline, by the time 90 percent of the initial residual has been removed, the remain compound consists of relatively insoluble and involatile constituents. This is an important aspect when setting up cleanup objectives for the project. Regulatory cleanup requirements are generally independent of the type of remediation. Soil vapor extraction may have to be used in conjunction with other forms of remediation to effect the proper cleanup of a contaminated site.

3.3.2 System Design, Operation, and Monitoring

The design and operation of soil vapor extraction systems is very flexible, allowing for changes to be made during the course of operation. Well placement can be changed, blower sizes altered, and air flow from injection wells varied in order to make the system operate more effectively. There is no one generic design procedure which will address all the possible variables that can be encountered at a particular site. More often than not, experience plays a critical role in the design and operation of this type of a remediation system. However, there are several common areas that need to be addressed on every project and these are discussed below.

3.3.2.1 Number of Extraction Wells

Two methods are given for calculating the number of extraction wells required at a site. Whichever method gives the largest number of wells is the value which should be used. The first method uses a ratio of removal rates as shown below:

$$N_{\text{wells}} = R_{\text{acceptable}} / R_{\text{est}}$$

where $R_{\text{acceptable}}$ is as previously defined and R_{est} is the estimated removal rate for a single well. The capacity of the blowers or vacuum pumps which are available must be taken into account since this may limit single well removal rates.

The second method takes into account the removal of all residuals from the entire contaminated zone in predicting the minimum number of wells required. This method uses a ratio of the area of contamination to the area of influence for a single well as shown below:

$$N_{\text{min}} = A_{\text{contamination}} / \pi R_I^2$$

This requires an estimate of the radius of influence, R_I , which defines the zone in which vapor flow is induced. This is typically measured during air permeability testing at the site. Generally, the radius of influence will depend on soil properties in the contaminated zone, the depth at which the well is screened, and the presence of impermeable boundaries like a clay layer or the water table. Typical values range from 10-100 feet. Kuo et al. (1990) developed a numerical model to estimate the radius of influence. They found that the radius was greatest when the ratio k_r/k_z equaled infinity, where k_r is the permeability in the radial direction and k_z is the permeability in the vertical direction. The radius of influence is generally proportional to this ratio.

3.3.2.2 Extraction Well Location

The critical factor in establishing the location of extraction wells is an understanding of the vapor flow behavior at the site. Locations should be chosen that ensure air flow through the contaminated zone, particularly the highest concentration areas, while minimizing flow through uncontaminated zones. If the area is small enough for one well, it should typically be located in the center of the site. This assumes that the concentration gradient is radial and that the vapor flow path is fairly consistent. When multiple wells are used, each well can impact the vapor flow of all the other wells and this will have to be considered when deciding on well locations. This problem is usually solved by installing air inlet wells, either passive or active, which will allow the system operator to change the vapor flow path to cover all areas within the contaminated zone. This problem can also be minimized by varying the vapor flow in each well over time. For air inlet wells to work effectively, they must be placed within the radius of influence of the extraction well. Care should also be taken to make sure that if active or injection type inlet wells are used, the vapor flow is toward the extraction well of concern and not away from the site. Air inlet wells can also be used as barriers to the migration of contaminants from off-site.

Vertical wells are not the only configuration for extraction wells. If the contamination is shallow; i.e. 10-15 feet, horizontal extraction trenches can be very effective in removing contaminants. A typical system consists of a perforated pipe placed in a trench and backfilled with a porous medium. The perforated pipe is then attached to a normal vapor extraction and treatment system. A barrier is typically placed over the porous medium to prevent air flow directly down the trench. Depending on the location of the contaminated zone, surface seals may be needed to

ensure air flow through the contaminated zone. The advantages of a horizontal extraction well include a greater effective radius with less applied vacuum, sites with high water tables can be remediated, ground water uplift is negligible, and it is easier to remediate contamination under buildings. Disadvantages are that it is difficult to remediate deep contamination's and the trenches generate more contaminated soil requiring treatment and disposal (Zappia et al. 1991).

3.3.2.3 Well Size and Screening

Typical extraction wells are constructed similar to monitoring wells with a 2-4 inch diameter well casing. Johnson (1990) showed that an increase in the diameter of a well from 4 to 8 inches increased the vapor flow rate by 15 percent. The well size should be as large as possible in order to increase the flow rate. One should remember that this increased well size will increase well construction costs and require the blower size to be increased to maintain the same flow rate. The benefits of increased performance due to a large well should be weighed against the increased construction and equipment cost to determine the most efficient and cost-effective system.

The screened length of the well casing should typically be within the contamination zone. Gamliel and Abdul (1992) demonstrated in modeling simulations that the length of the screen was linear with the radius of influence of an extraction well which suggests that the screen length should be as large as possible to increase the production of the extraction well. However, having the screen above the contaminated zone may promote air flow short-circuiting which in turn will reduce the system efficiency. The only time the well should be screened above the contaminated zone is if the permeability to vapor flow is so low that removal rates would be greater if flow were induced in an adjacent layer.

3.3.2.4 Operation and Monitoring

For most vapor extraction remediation projects, the initial contaminant recovery rate will be very high but will quickly drop off and remain at a low level for the duration of the project. One means of increasing the efficiency at the site is to use intermittent pumping from individual wells. This technique can be more effective in terms of mass of contaminant removed per unit of energy expended. This is especially true when extracting from soils where mass-transfer is limited by diffusion out of immobile air and water. This type of operation may involve taking individual wells in and out of service to allow time for gas diffusion.

The performance of a soil vapor extraction system must be monitored on a regular basis in order to ensure optimum removal of contaminants and to determine when to shut off the system. Measurements which should be taken on a regular basis include the ambient and soil temperature, water table levels to ensure that contaminated soil remains exposed to vapor flow. As discussed previously, placing a vacuum on an extraction well will raise the level of the water table which can be detrimental to vapor flow. Measuring the water level will require a special cap since uncapping the extraction well would release the vacuum on the system and effect water level measurements.

Vapor flow rates from the extraction well should be measured and recorded by flow meters as well as pressure readings from the extraction and inlet wells. Vapor concentrations and composition from the extraction wells should be measured by field gas chromatographs. This information along with the vapor flow rate data can be used to calculate removal rates and the volume of contaminant removed. The vapor composition should be checked periodically to determine if the reductions in

concentration are due to composition changes or problems with the operating system. The soil gas vapor concentrations should also be measured at different radial distances from the extraction well. This can be done by extracting samples from monitoring wells around the site or by using soil gas survey probes. Survey probes offer the advantage of flexibility in obtaining information about the site at various locations which can be used to determine if the contamination zone is shrinking.

3.3.2.5 When Should the System be Turned Off?

One of the major problems in the operation of a soil vapor extraction system is determining when the site is sufficiently clean by regulatory standards to be turned off. Several parameters are typically evaluated to determine if the site is clean.

- Volume removed: This is determined by multiplying the measured removal rate by the elapsed time. This method is only valid when the original spill volume is accurately known.

- Extraction well vapor concentrations: This is a good indication of the effectiveness of the system but decreasing vapor concentration may be due to systems problems such as rising water tables, leaking extraction components, mass transfer resistance, or pore blockage.

- Extraction vapor composition: When combined with vapor concentration, this data offers a better picture of the extent of cleanup accomplished. If the vapor concentration decreases, it may be due to one of the previously mentioned problems. If the concentration decreases along with a change in the vapor composition to a less volatile constituent, then this is most likely due to a reduction in the volume of the contaminant.

-Soil gas concentrations and composition: This is probably the most useful data about cleanup levels because it gives direct information about the remaining residual and the extent of contamination. This is accomplished by extracting gas samples with soil probes and obtaining soil borings for head space analysis.

-Intermittent operation: A fairly simple test of the level of decontamination is to intermittently operate the system near the end of the cleanup. If the vapor concentrations don't increase after restarting the system, one may assume the site has been decontaminated.

-Health risk assessment: Vapor extraction systems will never return the site to pristine conditions. Typically, these systems will continue to remove low concentrations of contaminants for years if operated that long. One possible solution to meeting regulatory requirements may be to perform a health risk assessment. If it can be demonstrated that the low levels of contamination will not pose a significant risk, the regulatory agencies overseeing the cleanup may approve ceasing operations even if contaminant concentration levels in the soil have not reach regulatory limits.

3.4 Concerns and Pitfalls of Soil Vapor Extraction Systems

Often times with soil remediation projects, the expectations are that technologies applied for removing contaminants will return the site to conditions where zero contamination exists i.e. "pristine conditions". This perception is typical among owners and facility operators who have limited remediation experience. Their major concern is to get rid of the problem completely at the lowest possible cost. Remediation technologies such as pump and treat and bioremediation are often only successful in source control and some reduction in contaminant concentration levels. It

is almost impossible, due to heterogenities, to reduce contamination levels to zero.

Soil vapor extraction is no different and will not completely clean a site.

Soil vapor extraction works best on highly volatile contaminants in granular, dry soils at locations where the water table is fairly deep. Variations in soil conditions, such as clay and silt layers and pockets, make predicting vapor flow paths extremely difficult. Sites with large amounts of clays and silts have typically not been candidates for vapor extraction because of the low air permeability and high organic content. This is not to say that they can't be cleaned up by this technology. The engineer must recognize in these areas that the advection process which makes vapor extraction successful in the early stages of most cleanup projects will be limited and diffusion will be the main means of mass transfer. This will greatly increase the time required for cleanup. Intermittent operation can often times increase the removal rate per unit of energy expended in these situations and be cost effective. Certain organic chemicals actually react with the clay, forming a more granular particle similar to a fine sand and increase the air permeability in the contaminated area. This effect would concentrate the air flow through the contaminated area and actually enhance remediation. Additionally, soil vapor extraction is typically only used on the lighter volatile organics such as gasoline and trichloroethylene. Heavier contaminants such as fuel oils and diesel fuel are generally not remediated by vapor extraction successfully.

When operating a vapor extraction system, several situations arise which must be recognized and taken into account during the design phase to avoid operational problems. The negative pressures placed on the soil around the extraction well tend to raise the water table level. In many cases, contaminated soils lie just above the water table and they become saturated. The maximum rise will occur below the vapor

extraction well where the water table rise will be equal to the vacuum at that point expressed as an equivalent water column height. The solution to this problem is to install a dewatering system with ground water pumping wells located as close to the extraction wells as possible. Since the water table is more than likely also contaminated, pump and treat operations may be a part of the larger site remediation plan and can be used for both purposes.

It is possible that venting will induce the migration of off-site contaminant vapors toward the extraction wells. This may occur in a heavily industrialized area with multiple contaminated zones or at service stations where other service stations are in the vicinity. If this occurs, one could spend large sums of money cleaning up someone else's contamination. This is solved by creating a vapor barrier around the perimeter of the site. This is accomplished by installing air inlet wells, either passive or active as necessary, to control the source of vapor flow to the wells.

4.0 Enhancement Technologies for Soil Vapor Extraction Systems

4.1 Introduction

Soil vapor extraction can be a very effective technology for the removal of volatile organic compounds in the vadose zone. This technology takes advantage of the highly volatile nature of the contaminant and the relative ease of moving air through the unsaturated zone. However, as discussed in Chapter Three, several limitations exist to the application of this technology. Soil vapor extraction only works effectively on relatively highly volatile organics. Contaminants such as diesel fuels and fuel oils do not have high enough vapor pressures to allow vapor extraction to efficiently clean up the site to acceptable levels. Also, this technology only works effectively in the vadose zone. Contaminants which have migrated into the saturated zone don't volatilize by typical injection air flow and are not removed by soil vapor extraction. Because protection of ground water is the principle goal of any remediation project, this shortfall in this application can severely limit vapor extraction as a viable means of waste site remediation. Since pump and treat technologies have demonstrated limited success in cleaning up contaminated soil in the saturated zone and groundwater, new cleanup methods need to be applied to address these problems. Secondly, soil vapor extraction can be a relatively inexpensive in situ technique. If less volatile contaminants could be partitioned from the soil to the vapor phase in the vadose zone; or if dissolved contaminants beneath the water table could be volatilized and transported into the vadose zone to be recovered, soil vapor extraction could find even more widespread applications.

Several new technologies have arisen in the last few years which may enhance soil vapor extraction to the point where it can be applied in previously unsuitable situations. These include air sparging, steam injection, and soil heating by propagation of radio frequency waves. Air sparging injects air below the groundwater surface to promote the volatilization of VOCs from the groundwater into the vadose zone so that they can be removed by the extraction system. Steam injection injects steam into the vadose zone to increase the subsurface temperature and volatilize contaminants with lower vapor pressures. Radio frequency soil heating applies electromagnetic energy to the soil which increases the volatilization of contaminants.

4.2 Air Sparging

Air sparging is a treatment technology which removes VOCs from the saturated zone. Contaminant free air is injected into contaminated groundwater to remove contaminants from the saturated zone and effectively capture them with a soil vapor extraction system (Figure 4.1). Air sparging essentially creates a crude air stripper in the subsurface, with the saturated soil column acting as the packing. Injected air flows through the water column over the packing, and air bubbles contacting contaminants cause the VOC to volatilize and be carried by the air bubbles into the vadose zone. Additionally, the sparged air maintains high dissolved oxygen levels which enhances natural biodegradation. The use of an air sparging system results in a net positive pressure in the subsurface, which must be compensated for by the extraction system to prevent migration to uncontaminated areas. Without soil vapor extraction, uncontrolled vapor flow may enter basements of nearby buildings and other low pressure areas, creating hazardous conditions.

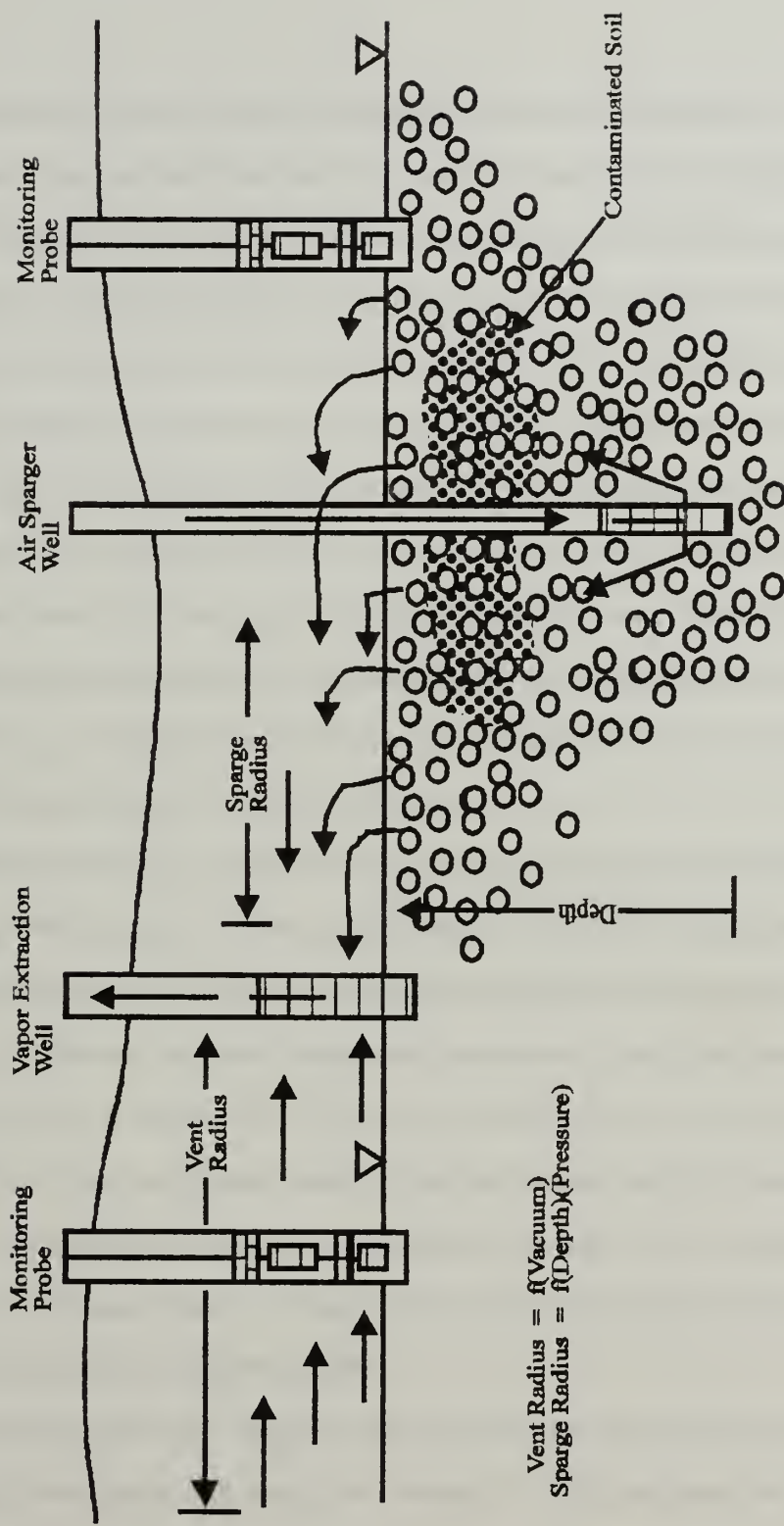


Figure 4.1 Diagram of Air Sparger System

The effectiveness of the air sparging system can be attributed to two major mechanisms; contaminant mass transport and biodegradation. Depending on the system configuration, operating parameters, and the type of contaminant, one of these mechanisms usually predominates or can be enhanced to optimize removal. The mass transfer mechanism consists of movement of contaminant in the subsurface and eventual extraction. Contaminants adsorbed to soils in the saturated zone dissolve into groundwater. The sparged air displaces water in the soil pore spaces and causes the soil contaminant to desorb, volatilize, and enter the saturated zone vapor phase. The mechanical action of the air passing through the saturated zone increases turbulence and mixing in the groundwater. Dissolved groundwater contaminant also volatilizes and migrates up through the aquifer to the unsaturated zone where the extraction system pulls the vapors to the extraction wells.

Biodegradation of contaminants by microorganisms requires the presence of sufficient carbon source, nutrients, and oxygen. Air sparging increases the oxygen content of the groundwater, which enhances biodegradation in the subsurface. The organic contaminants, especially petroleum constituents, provide the carbon source (Noonan, Glynn, & Miller 1993). If the rate of biodegradation is to be significantly enhanced, nutrients such as nitrogen and phosphorous may need to be added. However, care should be taken when supplanting nutrients into the subsurface. Excessive biological growth may occur which can foul the injection wells and reduce the effectiveness of the sparging system.

The design of an air sparging system involves selecting the well configuration, blower and compressor sizes which are combined with the parameters of the soil vapor

extraction system. The following information is needed for an effective air sparging system:

- The location of potential groundwater and vapor receptors.
- The geological conditions at the site.
- The contaminant mass distribution within the area to be treated in both soil and groundwater.
- The radius of influence of the sparge wells at various flow rates/pressures.

The ease and affordability of installing small-diameter air injection points allows considerable flexibility in the design and construction of a remediation system. The ability to install a dense grid of injection points without major site disruption or expense means that many of the problems associated with stagnate zones in the contaminated zone can be avoided by simply covering the entire area with injection points which overlap each other. Construction of the air injection points allows the designer to precisely target the aeration effect with fairly short well screens at specific depths. If site investigations identify high concentration zones or soil heterogeneities, injection points may be accurately placed to concentrate remediation activities in this specific zone.

The spacing configuration generally applied for air sparging systems is a square grid pattern with the extraction well in the center and the injection points at the corners. This pattern works well for sites with highly uniform sandy soils where an effective air flow pattern can be established between the injection and extraction wells. The spacing of the wells is based on the radius of influence of the extraction and sparging. Nested wells are extraction and sparging wells placed in the same borehole. This configuration can reduce the drilling cost but care must be taken during

installation to ensure that the borehole is properly grouted to prevent short-circuited air flow. The pressure gradient for this type of configuration is generally in the vertical direction. Nesting works better for sites with highly stratified silty soils where the vertical permeability is less than the horizontal permeability. Horizontal wells may be used for air sparging by installing perforated pipes with gravel packs in a trench. The horizontal configuration provides a more uniform pressure gradient at specific depths over a wider area. Trenches are particularly well suited to sites with a shallow water table and long narrow contaminated zones like leaking pipelines.

The implementation of an air sparging system must take into account changes that may occur in the subsurface. The introduction of air below the water table will cause an increase in the groundwater elevation, which is known as mounding. This effect, if not properly controlled, may cause the migration of contaminants away from the treatment area and when coupled with the rise due to the vacuum from the extraction well, could submerge the extraction well screen. Sparging can also cause dissolved minerals to precipitate, thereby impeding the flow of air through the subsurface. Careful monitoring of the air injection rate is necessary in order to minimize these effects.

4.3 Steam Injection

Steam injection is an in situ treatment technology for the removal of VOCs in the subsurface. Steam is injected into a contaminated zone to thermally recover volatile and semi-volatile contaminants in conjunction with water and vapor extraction (Figure 4.2). Steam injection is coupled with a soil vapor extraction system and a water extraction system in order to capture the contaminants that are liberated from

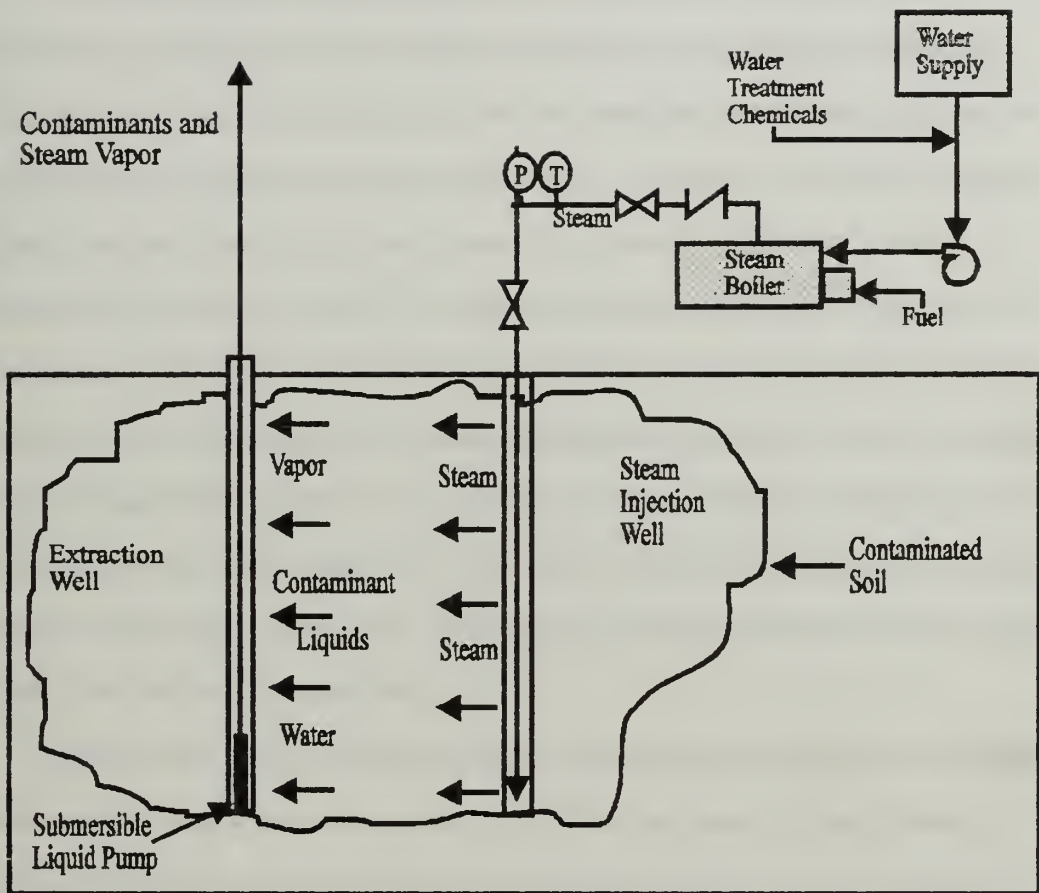


Figure 4.2 Schematic of a steam injection system.

the soil. The use of steam injection results in the migration of vapors in the steam zone and the flow of contaminated liquids ahead of the steam condensation front.

The effectiveness of steam injection is attributed to two mechanisms; vaporization of volatile and semi-volatile contaminants, and the displacement of liquids. As the steam is initially injected into the subsurface, the ambient soils remove the latent heat of vaporization from the steam and it condenses. As additional steam is injected, the condensate front moves outward from the injection point and an isothermal steam zone is created. The zone beyond the steam front is referred to as a variable temperature zone. Low boiling point liquids in the range of 90°C-150°C will generally be mobilized ahead of the steam condensate front in the variable temperature zone and accumulate in both the vapor and liquid phase. Organic contaminants with low vapor pressures may remain in the pore spaces within the isothermal steam zone. However, continued steam injection will evaporate these contaminant or enhance their migration toward the extraction wells.

The removal of residual petroleum at a contaminated site can be accomplished over the entire contaminated area or sequentially in small areas. Although energy intensive to operate, a steam injection system need only work a fraction of the time required for more conventional remediation techniques; i.e. on the order of weeks instead of months for traditional remediation methods (Noonan, Glynn, & Miller 1993). When considering this technology for cleanup of a site, a reasonable cleanup time must be estimated based on site condition such as the extent of contamination and soil permeability in order to develop a comparable cost estimate.

Similar to air sparging, the major factors affecting the radius of influence of a steam injection system are soil permeability, steam injection pressure, and the steam

flow rates. Generally, higher permeability soils will have a larger radius of influence for steam injection with a typical range of 25 ft to 100 ft from the injection point. The radius of influence for the steam injection system will determine the well spacing and number of wells needed for the site. If a faster cleanup time is required, the injection wells can be spaced closer together than the maximum distance in order to heat the subsurface more quickly.

Steam injection has been used to remove contaminants in both the saturated and unsaturated zones. In general, the amount of steam required in the saturated zone is about four to five greater than that required for the unsaturated zone. The additional heat is required to displace, heat, and vaporize the groundwater. However, the cleanup time and costs are still significantly less than those required for groundwater pump and treat systems.

The operation of a steam injection system begins with the injection of steam and extraction of liquid and vapors at the same time. During the first stage of operation, the subsurface is heated to the steam temperature as the steam front moves toward the extraction wells. After the injected steam breaks through to the extraction well, steam injection continues until the contaminant concentration approaches the cleanup objectives. At that point, steam injection is stopped while the soil vapor extraction system continues to operate which will continue to vaporize the residual contaminant in the pore spaces and dry out the soil.

4.4 Radio Frequency Heating

The radio frequency in situ heating method is a technique for rapid and uniform heating of large volumes of soil. This method can increase the soil temperature from

50°C-200°C. As discussed previously, raising the temperature can enhance the volatilization of contaminants with lower vapor pressures which would typically not be candidates for soil vapor extraction. Because the soil is heated in a uniform manner, a more consistent decontamination of the soil can be accomplished than with typical extraction methods which use boreholes placed around the site to extract vapors. Another advantage of in situ heating is that if soil moisture has reduced the air permeability, this method can be used to reduce the moisture content and increase the effectiveness of soil vapor extraction.

Radio frequency heating is performed by applying electromagnetic energy in the radio frequency band. The principles are similar to those of a microwave oven, except the frequency of operation is different and the size of the application is much larger. The temperature rise is due to ohmic and dielectric heating mechanisms. Ohmic heating occurs when an ionic or conduction current flows in the material in response to the applied electric field similar to the current flow in a light bulb. Dielectric heating occurs from the physical distortion of the molecular structure of polar materials in response to an applied electric field. Since the AC electric field changes rapidly, the alternating physical distortion dissipates mechanical energy which is translated into thermal energy in the soil. This technology was first developed by the oil industry for recovery of additional petroleum products.

A radio frequency heating system contains three components; the RF energy deposition electrode array, the RF power generation system, and the soil vapor extraction system. The critical factor in the design of an RF heating system is the electrode array. Typically, the electrodes are inserted on the perimeter and in the center of the contaminated site in parallel rows. The most important parameter that

must be addressed by the designer is the location, row spacing and electrode spacing within each row of the array. This will influence how efficiently the energy required for power generation is used in heating the soil.

5.0 Conclusion

VOC contamination of soil and groundwater exists at thousands of sites nationwide. Soil vapor extraction has been successfully used to remediate a wide range of contaminants at many of these sites with cost savings over other remediation techniques such as excavation and treatment and disposal, soil capping and soil flushing. The key to determining if soil vapor extraction will work is a thorough site characterization and feasibility study based on the technical, economic, regulatory and political issues specific to each individual site.

The first step in any remediation project is a thorough site investigation and characterization. The designer must know and understand the condition of the site in order to make rational decisions about treatment options. A soil vapor survey using driven probes is an excellent tool for determining contaminant and site characteristics. Because of the relatively high cost of soil borings, the soil vapor survey should be used to optimize boring locations and to map the contaminant plumb at the site. The most important thing to remember about site characterization is that it must be thorough and complete. As engineers, we have an obligation to efficiently use our clients' money when remediating a contaminated site. The minimal savings made by limiting site testing and investigation during the beginning of a project can and often will cost more in actual cleanup costs and time because of the poor decisions that are made with the insufficient data available.

The design process is by no means rigid and unvarying. The design and operation of soil vapor extraction systems can be modified throughout the project in order to maximize the removal of contaminants. Each site has individual

characteristics which must be taken into account in order to optimize results.

Decisions will need to be made on well location, design, and spacing. Soil characteristics will play an important role in these decisions. Conditions in the soil may require passive or active air injection well to "feed" air to the contaminated zone and enhance volatilization. Installation of a cap over the area to be remediated may be required to extend the path that air follows from the ground surface, thereby increasing the volume of soil treated. Operation of the system will need to change as the characteristics of the contaminant change over the life to the project. Intermittent operation is often the most efficient use of equipment. This is particularly true when operating in less permeable soils such as clays and silts where diffusion is a more prevalent mass transfer mechanism.

Several methods are available to enhance the operation of soil vapor extraction systems. Typically, soil vapor extraction is not used for groundwater cleanup because contaminant removal is mainly accomplished by diffusion which is normally too slow for most remediation projects. Air sparging can be used to volatilize contaminants in the saturated zone and move them up to the unsaturated zone and may also enhance biodegradation. Less volatile contaminants may be volatilized by heating the soil by steam or radio frequency wave propagation. Steam may also be used to push the contaminant toward extraction.

Soil vapor extraction can be an effective technology for removing volatile contaminants over a wide range of conditions. Although it can be operated independently under certain conditions, it is more often used in conjunction with other treatment technologies to effect the cleanup of a contaminated site. Probably the most important advantage of soil vapor extraction is the flexibility it gives the designer in

adapting the system to a given set of site-specific conditions and the ability to modify the system in the field to optimize contaminant removal over the life of the project.

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